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Annex to the Request

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Applicant's or agent's file reference: FH980405PCT

Applicant: Fraunhofer-Gesellschaft ... et al

CALCULATION OF PRESCRIBED FEES

1. TRANSMITTAL FEE . . . . 200,00 [T]

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first 30 sheets			800,00	b_1
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2800 0601	April 14, 1998	SCHOPPE, Fritz

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Sheet No. ....5..

Box No. VI PRIORITY CLAIM Further priority claims are indicated in the Supplemental Box ☐

The priority of the following earlier application(s) is hereby claimed:

Country *(in which, or for which, the application was filed)*	Filing Date *(day/month/year)*	Application No.	Office of filing *(only for regional or international application)*
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Box No. VIII CHECK LIST

This international application contains the following number of sheets:

1. request	:	5	sheets
2. description	:	30	sheets
3. claims	:	13	sheets
4. abstract	:	1	sheets
5. drawings	:	4	sheets
Total	:	53	sheets

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4. ☐ priority document(s) *identified in Box No. VI as item(s):*
5. ☒ fee calculation sheet
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Figure No. Fig. 1 of the drawings (if any) should accompany the abstract when it is published.

Box No. IX SIGNATURE OF APPLICANT OR AGENT

Next to each signature, indicate the name of the person signing and the capacity in which the person signs (if such capacity is not obvious from reading the request).

Munich, April 14, 1998 SCHOPPE, Fritz

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1. Date of actual receipt of the purported international application:	2. Drawings: ☐ received: ☐ not received:
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METHOD AND APPARATUS FOR MULTI-CARRIER MODULATION AND DE-MODULATION AND METHOD AND APPARATUS FOR PERFORMING AN ECHO PHASE OFFSET CORRECTION ASSOCIATED THEREWITH

EO/US
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Date of mailing: 21 October 1999 (21.10.99)	
International application No.: PCT/EP98/02167	Applicant's or agent's file reference: FH980405PCT
International filing date: 14 April 1998 (14.04.98)	Priority date:
Applicant: EBERLEIN, Ernst et al	

1. The designated Office is hereby notified of its election made:

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2895114

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529 Rec'd PCT/PTO 13 OCT 2000

METHOD AND APPARATUS FOR MULTI-CARRIER MODULATION AND DE-MODULATION AND METHOD AND APPARATUS FOR PERFORMING AN ECHO PHASE OFFSET CORRECTION ASSOCIATED THEREWITH

FIELD OF THE INVENTION

The present invention relates to methods and apparatus for performing modulation and de-modulation in multi-carrier modulation systems (MCM systems) and, in particular, to methods and apparatus for differential mapping and de-mapping of information onto carriers of multi-carrier modulation symbols in such systems. Furthermore, the present invention relates to methods and apparatus for performing an echo phase offset correction when decoding information encoded onto carriers of multi-carrier modulation symbols in multi-carrier modulation systems.

BACKGROUND OF THE INVENTION

The present invention generally relates to broadcasting of digital data to mobile receivers over time-variant multipath channels. More specifically, the present invention is particularly useful in multipath environments with low channel coherence time, i.e. rapidly changing channels. In preferred embodiments, the present invention can be applied to systems implementing a multicarrier modulation scheme. Multi-carrier modulation (MCM) is also known as orthogonal frequency division multiplexing (OFDM).

In a MCM transmission system binary information is represented in the form of a complex spectrum, i.e. a distinct number of complex subcarrier symbols in the frequency domain. In the modulator a bitstream is represented by a sequence of spectra. Using an inverse Fourier-transform (IFFT) a MCM time domain signal is

produced from this sequence of spectra.

Figure 7 shows a MCM system overview. At 100 a MCM transmitter is shown. A description of such a MCM transmitter can be found, for example, in William Y. Zou, Yiyan Wu, "COFDM: AN OVERVIEW", IEEE Transactions on Broadcasting, vol. 41, No. 1, March 1995.

A data source 102 provides a serial bitstream 104 to the MCM transmitter. The incoming serial bitstream 104 is applied to a bit-carrier mapper 106 which produces a sequence of spectra 108 from the incoming serial bitstream 104. An inverse fast Fourier transform (FFT) 110 is performed on the sequence of spectra 108 in order to produce a MCM time domain signal 112. The MCM time domain signal forms the useful MCM symbol of the MCM time signal. To avoid intersymbol interference (ISI) caused by multipath distortion, a unit 114 is provided for inserting a guard interval of fixed length between adjacent MCM symbols in time. In accordance with a preferred embodiment of the present invention, the last part of the useful MCM symbol is used as the guard interval by placing same in front of the useful symbol. The resulting MCM symbol is shown at 115 in Figure 7.

A unit 116 for adding a reference symbol for each predetermined number of MCM symbols is provided in order to produce a MCM signal having a frame structure. Using this frame structure comprising useful symbols, guard intervals and reference symbols it is possible to recover the useful information from the MCM signal at the receiver side.

The resulting MCM signal having the structure shown at 118 in Figure 7 is applied to the transmitter front end 120. Roughly speaking, at the transmitter front end 120, a digital/analog conversion and an up-converting of the MCM signal is performed. Thereafter, the MCM signal is transmitted through a channel 122.

Following, the mode of operation of a MCM receiver 130 is shortly described referring to Figure 7. The MCM signal is received at the receiver front end 132. In the receiver front end 132, the MCM signal is down-converted and, furthermore, a digital/analog conversion of the down-converted signal is performed. The down-converted MCM signal is provided to a frame synchronization unit 134. The frame synchronization unit 134 determines the location of the reference symbol in the MCM symbol. Based on the determination of the frame synchronization unit 134, a reference symbol extracting unit 136 extracts the framing information, i.e. the reference symbol, from the MCM symbol coming from the receiver front end 132. After the extraction of the reference symbol, the MCM signal is applied to a guard interval removal unit 138.

The result of the signal processing performed so far in the MCM receiver are the useful MCM symbols. The useful MCM symbols output from the guard interval removal unit 138 are provided to a fast Fourier transform unit 140 in order to provide a sequence of spectra from the useful symbols. Thereafter, the sequence of spectra is provided to a carrier-bit mapper 142 in which the serial bitstream is recovered. This serial bitstream is provided to a data sink 144.

As it is clear from Figure 7, every MCM transmitter 100 must contain a device which performs mapping of the transmitted bitstreams onto the amplitudes and/or phases of the sub-carriers. In addition, at the MCM receiver 130, a device is needed for the inverse operation, i.e. retrieval of the transmitted bitstream from the amplitudes and/or phases of the sub-carriers.

For a better understanding of MCM mapping schemes, it is preferable to think of the mapping as being the assignment of one ore more bits to one or more sub-carrier symbols in the time-frequency plane. In the following, the term symbol

or signal point is used for the complex number which represents the amplitude and/or phase modulation of a subcarrier in the equivalent baseband. Whenever all complex numbers representing all subcarrier symbols are designated, the term MCM symbol is used.

DESCRIPTION OF PRIOR ART

In principle, two methods for mapping the bitstream into the time-frequency plane are used in the prior art:

A first method is a differential mapping along the time axis. When using differential mapping along the time axis one or more bits are encoded into phase and/or amplitude shifts between two subcarriers of the same center frequency in adjacent MCM symbols. Such an encoding scheme is shown in Figure 8. The arrows depicted between the sub-carrier symbols correspond to information encoded in amplitude and/or phase shifts between two subcarrier symbols.

A system applying such a mapping scheme is defined in the European Telecommunication Standard ETS 300 401 (EU147-DAB). A system compliant to this standard uses Differential Quadrature Phase Shift Keying (DQPSK) to encode every two bits into a 0, 90, 180 or 270 degrees phase difference between two subcarriers of the same center frequency which are located in MCM symbols adjacent in time.

A second method for mapping the bitstream into the time-frequency plane is a non-differential mapping. When using non-differential mapping the information carried on a subcarrier is independent of information transmitted on any other subcarrier, and the other subcarrier may differ either in frequency, i.e. the same MCM symbol, or in time, i.e. adjacent MCM symbols. A system applying such a mapping scheme is defined in the European Telecommunication Standard ETS 300 744 (DVB-T). A system compliant to this standard

uses 4,16 or 64 Quadrature Amplitude Modulation (QAM) to assign bits to the amplitude and phase of a subcarrier.

The quality with which transmitted multi-carrier modulated signals can be recovered at the receiver depends on the properties of the channel. The most interesting property when transmitting MCM signals is the time interval at which a mobile channel changes its characteristics considerably. The channel coherence time T_C is normally used to determine the time interval at which a mobile channel changes its characteristics considerably. T_C depends on the maximum Doppler shift as follows:

$$f_{Doppler,max} = v \cdot f_{carrier} \;/\; c \qquad \text{(Eq.1)}$$

with v : speed of the mobile receiver in [m/s]
$f_{carrier}$: carrier frequency of the RF signal [Hz]
c : speed of light ($3 \cdot 10^8$ m/s)

The channel coherence time T_C is often defined to be

$$T_c\big|_{50\%} = \frac{9}{16\pi f_{Doppler,max}} \quad \text{or} \quad T_c\big|_{2nd\ Def.} = \sqrt{\frac{9}{16\pi f^2_{Dopper,max}}} \qquad \text{(Eq.2)}$$

It becomes clear from the existence of more than one definition, that the channel coherence time Tc is merely a rule-of-thumb value for the stationarity of the channel. As explained above, the prior art time-axis differential mapping requires that the mobile channel be quasi stationary during several MCM symbols periods, i.e. required channel coherence time Tc >> MCM symbol period. The prior art non-differential MCM mapping only requires that the mobile channel be quasi stationary during one symbol interval, i.e. required channel coherence time ≥ MCM symbol period.

Thus, both prior art mapping schemes have specific disadvantages. For differential mapping into time axis direction the channel must be quasi stationary, i.e. the channel must not change during the transmission of two MCM

symbols adjacent in time. If this requirement is not met, the channel induced phase and amplitude changes between MCM symbols will yield an increase in bit error rate.

With non-differential mapping exact knowledge of the phase of each subcarrier is needed (i.e. coherent reception). For multipath channels, coherent reception can only be obtained if the channel impulse response is known. Therefore, a channel estimation has to be part of the receiver algorithm. The channel estimation usually needs additional sequences in the transmitted waveform which do not carry information. In case of rapidly changing channels, which necessitate update of the channel estimation at short intervals, the additional overhead can quickly lead to insufficiency of non-differential mapping.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method and an apparatus for mapping information onto sub-carrier symbols in a multi-carrier modulation system which allow correct recovering of the information after transmission through a channel even in the case the channel is not stationary during several MCM symbols.

It is a further object of the present invention to provide a method and an apparatus for performing a multi-carrier modulation of a bitstream in a digital broadcasting transmitter which allow correct recovering of the bitstream after transmission through a channel even in the case the channel is not stationary during several MCM symbols.

It is a further object of the present invention to provide a method and an apparatus for de-mapping information in order to correctly recover the information even in the case a channel through which transmission takes place is not stationary during several MCM symbols.

It is a further object of the present invention to provide a method and an apparatus for performing a demodulation of a multi-carrier modulated signal in a digital broadcasting system in order to correctly recover a bitstream encoded in the multi-carrier modulated signal even in the case a channel through which transmission takes place is not stationary during several MCM symbols.

It is a further object of the present invention to provide methods an apparatus for performing an echo phase offset correction in a multi-carrier demodulation system.

In accordance with a first aspect, the present invention provides a method of mapping information onto at least two simultaneous carriers having different frequencies in a multi-carrier modulation system, the method comprising the step of controlling respective parameters of the at least two carriers such that the information is differentially encoded.

In accordance with a second aspect, the present invention provides a method of performing a multi-carrier modulation of a bitstream in a digital broadcasting transmitter, the method comprising the steps of:

phase shift keying the bitstream by associating a respective phase shift to one or more bits of the bitstream; and

differential phase encoding the phase shifts by controlling the phase of a first carrier based on a phase of a simultaneous second carrier and the phase shift, the first and second carriers having different frequencies.

In accordance with a third aspect, the present invention provides a method of de-mapping information based on at least two simultaneous encoded carriers having different

frequencies in a multi-carrier demodulation system, the method comprising the step of recovering the information by differential decoding of respective parameters of the at least two carriers.

In accordance with a fourth aspect, the present invention provides a method of performing a demodulation of a multi-carrier modulated signal in a digital broadcasting system, the method comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

recovering bits of a bitstream from said phase shifts.

In accordance with a fifth aspect, the present invention provides a method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties corresponding to codeable phase shifts from the decoded phase shift;

averaging the echo phase offsets in order to generate an averaged offset; and

correcting each decoded phase shift based on the averaged offset.

In accordance with a sixth aspect, the present invention provides a method of performing an echo phase offset

correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

determining a phase offset based on the parameters; and

correcting each decoded phase shift based on the phase offset.

In accordance with a seventh aspect, the present invention provides a mapping device for mapping information onto at least two simultaneous carriers having different frequencies, for a multi-carrier modulation system, the device comprising means for controlling respective parameters of the at least two carriers such that the information is differential encoded.

In accordance with an eighth aspect, the present invention provides a multi-carrier modulator for performing a multi-carrier modulation of a bitstream, for a digital broadcasting transmitter, the modulator comprising:

means for phase shift keying the bitstream by associating a respective phase shift to one or more bits of the bit-stream; and

a differential phase encoder for differential phase

encoding the phase shifts by controlling the phase of a first carrier based on a phase of a simultaneous second carrier and the phase shift, the first and second carriers having different frequencies.

In accordance with a ninth aspect, the present invention provides a de-mapping device for de-mapping information based on at least two simultaneous encoded carriers having different frequencies, for a multi-carrier demodulation system, the de-mapping device comprising means for recovering the information by differential decoding of respective parameters of the at least two carriers.

In accordance with a tenth aspect, the present invention provides a demodulator for demodulating a multi-carrier modulated signal, for a digital broadcasting system, the demodulator comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for recovering bits of a bitstream from the phase shifts.

In accordance with an eleventh aspect, the present invention provides an echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties corresponding to codeable phase shifts from the decoded phase shift;

means for averaging the echo phase offsets in order to generate an averaged offset; and

means for correcting each decoded phase shift based on the averaged offset.

In accordance with a twelfth aspect, the present invention provides an echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

means for pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

means for determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

means for determining a phase offset based on the parameters; and

means for correcting each decoded phase shift based on the phase offset.

The present invention provides a mapping process, suitable for multicarrier (OFDM) digital broadcasting over rapidly changing multipath channels, comprising differential encoding of the data along the frequency axis such that there is no need for channel stationarity exceeding one multicarrier symbol.

When using the inventive mapping process along the frequency axis it is preferred to make use of a receiver algorithm that will correct symbol phase offsets that can be caused by

channel echoes.

The present invention provides a mapping scheme for multi-carrier modulation which renders the transmission to a certain extent independent of rapid changes in the multipath channel without introducing a large overhead to support channel estimation. Especially systems with high carrier frequencies and/or high speeds of the mobile carrying the receiving unit can benefit from the invention.

Thus, the present invention provides a mapping scheme that does not exhibit the two problems of the prior art systems described above. The mapping scheme in accordance with the present invention is robust with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

According to a preferred embodiment of the present invention, the controlled respective parameters of the subcarriers are the phases thereof, such that the information is differentially phase encoded. However, the controlled respective parameters of the subcarriers can be the amplitudes thereof as well, such that the information is differential amplitude encoded.

In accordance with the present invention, mapping is also differential, however, not into time axis direction but into frequency axis direction. Thus, the information is not contained in the phase shift between subcarriers adjacent in time but in the phase shift between subcarriers adjacent in frequency. Differential mapping along the frequency axis has two advantages when compared to prior art mapping schemes. Because of differential mapping, no estimation of the absolute phase of the subcarriers is required. Therefore, channel estimation and the related overhead are not necessary. By choosing the frequency axis as direction for differentially encoding the information bitstream, the requirement that the channel must be stationary during

several MCM symbols can be dropped. The channel only has to remain unchanged during the current MCM symbol period. Therefore, like for non-differential mapping it holds that

required channel coherence time $\geq$ MCM symbol period.

The present invention further provides methods and apparatus for correction of phase distortions that can be caused by channel echoes. As described above, differential mapping into frequency axis direction solves problems related to the stationarity of the channel. However, differential mapping into frequency axis direction may create a new problem. In multipath environments, path echoes succeeding or preceding the main path can lead to systematic phase offsets between subcarriers in the same MCM symbol. In this context, the main path is thought of being the path echo with the highest energy content. The main path echo will determine the position of the FFT window in the receiver of an MCM system.

In preferred embodiments of the present invention, the information will be contained in a phase shift between adjacent subcarriers of the same MCM symbol. If not corrected for, the path echo induced phase offset between two subcarriers can lead to an increase in bit error rate. Therefore, application of the MCM mapping scheme presented in this invention will preferably be used in combination with a correction of the systematic subcarrier phase offsets in case of a multipath channel.

The introduced phase offset can be explained from the shifting property of the Discrete Fourier Transform (DFT):

$$x\left[((n-m))_N\right] \xleftrightarrow{DFT} X[k]e^{-j\frac{2\pi}{N}km} \qquad \text{(Eq.3)}$$

with x[n] : sampled time domain signal ($0 \leq n \leq N-1$)

X[k] : DFT transformed frequency domain signal ($0 \leq k \leq N-1$)

N : length of DFT

$(\ldots)_N$: cyclic shift of the DFT window in the time
m : length of DFT-Shift in the time domain

Equation 3 shows, that in a multipath channel, echoes following the main path will yield a subcarrier dependent phase offset. After differential demapping in the frequency axis direction at the receiver, a phase offset between two neighboring symbols remains. Because the channel induced phase offsets between differentially demodulated symbols are systematic errors, they can be corrected by an algorithm.

In the context of the following specification, algorithms which help correcting the phase shift are called Echo Phase Offset Correction (EPOC) algorithms. Two such algorithms are described as preferred embodiments for the correction of phase distortions that can be caused by channel echoes. These algorithms yield a sufficient detection security for MCM frequency axis mapping even in channels with echoes close to the limits of the guard interval.

In principle, an EPOC algorithm must calculate the echo induced phase offset from the signal space constellation following the differential demodulation and subsequently correct this phase offset.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following, preferred embodiments of the present invention will be explained in detail on the basis of the drawings enclosed, in which:

Figure 1 shows a schematic view representing the inventive mapping scheme;

Figure 2 shows a functional block diagram of an embodiment of a mapping device in accordance with the present invention;

Figures 3A and 3B show scatter diagrams of the output of an differential de-mapper of a MCM receiver for illustrating the effect of an echo phase offset correction;

Figure 4 shows a schematic block diagram for illustrating the position and the functionality of an echo phase offset correction unit;

Figure 5 shows a schematic block diagram of an embodiment of an echo phase offset correction device according to the present invention;

Figure 6 shows schematic views for illustrating a projection performed by another embodiment of an echo phase offset correction device according to the present invention;

Figure 7 shows a schematic block diagram of a generic multi-carrier modulation system; and

Figure 8 shows a schematic view representing a prior art differential mapping scheme.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Although the present invention is explained mainly referring to a MCM system using differential phase encoding as generally shown in Figure 7, it is clear that the present invention can be used in connection with different transmission systems using differential amplitude encoding or a combined differential amplitude/phase encoding, for example.

In a preferred embodiment thereof, the present invention is applied to a MCM system as shown in Figure 7. With respect

to this MCM system, the present invention relates to the bit-carrier mapper 106 of the MCM transmitter 100 and the carrier-bit mapper 142 of the MCM receiver 130, which are depicted with a shaded background in Figure 7.

An preferred embodiment of an inventive mapping scheme used by the bit-carrier mapper 106 is depicted in Figure 1. A number of MCM symbols 200 is shown in Figure 1. Each MCM symbol 200 comprises a number of sub-carrier symbols 202. The arrows 204 in Fig. 1 illustrate information encoded between two sub-carrier symbols 202. As can be seen from the arrows 204, the bit-carrier mapper 106 uses a differential mapping within one MCM symbol along the frequency axis direction.

In the embodiment shown in Figure 1, the first sub-carrier (k=0) in an MCM symbol 200 is used as a reference sub-carrier 206 (shaded) such that information is encoded between the reference sub-carrier and the first active carrier 208. The other information of a MCM symbol 200 is encoded between active carriers, respectively.

Thus, for every MCM symbol an absolute phase reference exists. In accordance with Figure 1, this absolute phase reference is supplied by a reference symbol inserted into every MCM symbol (k=0). The reference symbol can either have a constant phase for all MCM symbols or a phase that varies from MCM symbol to MCM symbol. A varying phase can be obtained by replicating the phase from the last subcarrier of the MCM symbol preceding in time.

In Figure 2 a preferred embodiment of a device for performing a differential mapping along the frequency axis is shown. Referring to Figure 2, assembly of MCM symbols in the frequency domain using differential mapping along the frequency axis according to the present invention is described.

Figure 2 shows the assembly of one MCM symbol with the following parameters:

N_{FFT} designates the number of complex coefficients of the discrete Fourier transform, number of subcarriers respectively.

K designates the number of active carriers. The reference carrier is not included in the count for K.

According to Figure 2, a quadrature phase shift keying (QPSK) is used for mapping the bitstream onto the complex symbols. However, other M-ary mapping schemes (MPSK) like 2-PSK, 8-PSK, 16-QAM, 16-APSK, 64-APSK etc. are possible.

Furthermore, for ease of filtering and minimization of aliasing effects some subcarriers are not used for encoding information in the device shown in Figure 2. These subcarriers, which are set to zero, constitute the so-called guard bands on the upper and lower edges of the MCM signal spectrum.

At the input of the mapping device shown in Figure 2, complex signal pairs b0[k], b1[k] of an input bitstream are received. K complex signal pairs are assembled in order to form one MCM symbol. The signal pairs are encoded into the K differential phase shifts phi[k] needed for assembly of one MCM symbol. In this embodiment, mapping from Bits to the 0, 90, 180 and 270 degrees phase shifts is performed using Gray Mapping in a quadrature phase shift keying device 220.

Gray mapping is used to prevent that differential detection phase errors smaller than 135 degrees cause double bit errors at the receiver.

Differential phase encoding of the K phases is performed in a differential phase encoder 222. At this stage of processing, the K phases phi[k] generated by the QPSK Gray

mapper are differentially encoded. In principal, a feedback loop 224 calculates a cumulative sum over all K phases. As starting point for the first computation (k = 0) the phase of the reference carrier 226 is used. A switch 228 is provided in order to provide either the absolute phase of the reference subcarrier 226 or the phase information encoded onto the preceding (i.e. z^{-1}, where z^{-1} denotes the unit delay operator) subcarrier to a summing point 230. At the output of the differential phase encoder 222, the phase information theta[k] with which the respective subcarriers are to be encoded is provided. In preferred embodiments of the present invention, the subcarriers of a MCM symbol are equally spaced in the frequency axis direction.

The output of the differential phase encoder 222 is connected to a unit 232 for generating complex subcarrier symbols using the phase information theta[k]. To this end, the K differentially encoded phases are converted to complex symbols by multiplication with

$$\text{factor} * e^{j*[2*pi*(theta[k] + PHI)]} \qquad \text{(Eq.4)}$$

wherein factor designates a scale factor and PHI designates an additional angle. The scale factor and the additional angle PHI are optional. By choosing PHI = 45° a rotated DQPSK signal constellation can be obtained.

Finally, assembly of a MCM symbol is effected in an assembling unit 234. One MCM symbol comprising N_{FFT} subcarriers is assembled from N_{FFT}-K-1 guard band symbols which are "zero", one reference subcarrier symbol and K DQPSK subcarrier symbols. Thus, the assembled MCM symbol 200 is composed of K complex values containing the encoded information, two guard bands at both sides of the N_{FFT} complex values and a reference subcarrier symbol.

The MCM symbol has been assembled in the frequency domain. For transformation into the time domain an inverse discrete

Fourier transform (IDFT) of the output of the assembling unit 234 is performed by a transformator 236. In preferred embodiments of the present invention, the transformator 236 is adapted to perform a fast Fourier transform (FFT).

Further processing of the MCM signal in the transmitter as well as in the receiver is as described above referring to Figure 7.

At the receiver a de-mapping device 142 (Figure 7) is needed to reverse the operations of the mapping device described above referring to Figure 2. The implementation of the demapping device is straightforward and, therefore, need not be described herein in detail.

However, systematic phase shifts stemming from echoes in multipath environments may occur between subcarriers in the same MCM symbol. This phase offsets can cause bit errors when demodulating the MCM symbol at the receiver.

Thus, it is preferred to make use of an algorithm to correct the systematic phase shifts stemming from echoes in multipath environments. Preferred embodiments of echo phase offset correction algorithms are explained hereinafter referring to Figures 3 to 6.

In Figures 3A and 3B, scatter diagrams at the output of a differential demapper of a MCM receiver are shown. As can be seen from Figure 3A, systematic phase shifts between subcarriers in the same MCM symbol cause a rotation of the demodulated phase shifts with respect to the axis of the complex coordinate system. In Figure 3B, the demodulated phase shifts after having performed an echo phase offset correction are depicted. Now, the positions of the signal points are substantially on the axis of the complex coordinate system. These positions correspond to the modulated phase shifts of 0°, 90°, 180° and 270°, respectively.

An echo phase offset correction algorithm (EPOC algorithm) must calculate the echo induced phase offset from the signal space constellation following the differential demodulation and subsequently correct this phase offset.

For illustration purposes, one may think of the simplest algorithm possible which eliminates the symbol phase before computing the mean of all phases of the subcarriers. To illustrate the effect of such an EPOC algorithm, reference is made to the two scatter diagrams of subcarriers symbols contained in one MCM symbol in Figures 3A and 3B. This scatter diagrams have been obtained as result of an MCM simulation. For the simulation a channel has been used which might typically show up in single frequency networks. The echoes of this channel stretched to the limits of the MCM guard interval. The guard interval was chosen to be 25% of the MCM symbol duration in this case.

Figure 4 represents a block diagram for illustrating the position and the functionality of an echo phase offset correction device in a MCM receiver. The signal of a MCM transmitter is transmitted through the channel 122 (Figures 4 and 7) and received at the receiver frontend 132 of the MCM receiver. The signal processing between the receiver frontend and the fast Fourier transformator 140 has been omitted in Figure 4. The output of the fast Fourier transformator is applied to the de-mapper, which performs a differential de-mapping along the frequency axis. The output of the de-mapper are the respective phase shifts for the subcarriers. The phase offsets of this phase shifts which are caused by echoes in multipath environments are visualized by a block 400 in Figure 4 which shows an example of a scatter diagram of the subcarrier symbols without an echo phase offset correction.

The output of the de-mapper 142 is applied to the input of an echo phase offset correction device 402. The echo phase

offset correction device 402 uses an EPOC algorithm in order to eliminate echo phase offsets in the output of the de-mapper 142. The result is shown in block 404 of Figure 4, i.e. only the encoded phase shifts, 0°, 90°, 180° or 270° are present at the output of the correction device 402. The output of the correction device 402 forms the signal for the metric calculation which is performed in order to recover the bitstream representing the transmitted information.

A first embodiment of an EPOC algorithm and a device for performing same is now described referring to Figure 5.

The first embodiment of an EPOC algorithm starts from the assumption that every received differentially decoded complex symbol is rotated by an angle due to echoes in the multipath channel. For the subcarriers equal spacing in frequency is assumed since this represents a preferred embodiment of the present invention. If the subcarriers were not equally spaced in frequency, a correction factor would have to be introduced into the EPOC algorithm.

Figure 5 shows the correction device 402 (Figure 4) for performing the first embodiment of an EPOC algorithm.

From the output of the de-mapper 142 which contains an echo phase offset as shown for example in Figure 3A, the phase shifts related to transmitted information must first be discarded. To this end, the output of the de-mapper 142 is applied to a discarding unit 500. In case of a DQPSK mapping, the discarding unit can perform a "$(.)^4$" operation. The unit 500 projects all received symbols into the first quadrant. Therefore, the phase shifts related to transmitted information is eliminated from the phase shifts representing the subcarrier symbols. The same effect could be reached with a modulo-4 operation.

Having eliminated the information related symbol phases in unit 500, the first approach to obtain an estimation would

be to simply compute the mean value over all symbol phases of one MCM symbol. However, it is preferred to perform a threshold decision before determining the mean value over all symbol phases of one MCM symbol. Due to Rayleigh fading some of the received symbols may contribute unreliable information to the determination of the echo phase offset. Therefore, depending on the absolute value of a symbol, a threshold decision is performed in order to determine whether the symbol should contribute to the estimate of the phase offset or not.

Thus, in the embodiment shown in Fig. 5, a threshold decision unit 510 is included. Following the unit 500 the absolute value and the argument of a differentially decoded symbol is computed in respective computing units 512 and 514. Depending on the absolute value of a respective symbol, a control signal is derived. This control signal is compared with a threshold value in a decision circuit 516. If the absolute value, i.e. the control signal thereof, is smaller than a certain threshold, the decision circuit 516 replaces the angle value going into the averaging operation by a value equal to zero. To this end, a switch is provided in order to disconnect the output of the argument computing unit 514 from the input of the further processing stage and connects the input of the further processing stage with a unit 518 providing a constant output of "zero".

An averaging unit 520 is provided in order to calculate a mean value based on the phase offsets φ_i determined for the individual subcarrier symbols of a MCM symbol as follows:

$$\overline{\varphi} = 1/K \sum_{i=1}^{K} \varphi_i \qquad \text{(Eq.5)}$$

In the averaging unit 520, summation over K summands which have not been set to zero in the unit 516 is performed. The output of the averaging unit 520 is provided to a hold unit

522 which holds the output of the averaging unit 520 K times. The output of the hold unit 522 is connected with a phase rotation unit 524 which performs the correction of the phase offsets of the K complex signal points on the basis of the mean value $\overline{\varphi}$.

The phase rotation unit 524 performs the correction of the phase offsets by making use of the following equation:

$$v_k' = v_k \cdot e^{-j\overline{\varphi}} \qquad \text{(Eq.6)}$$

In this equation, v_k' designates the K phase corrected differentially decoded symbols for input into the soft-metric calculation, whereas v_k designates the input symbols. As long as a channel which is quasi stationary during the duration of one MCM symbols can be assumed, using the mean value over all subcarriers of one MCM symbol will provide correct results.

A buffer unit 527 may be provided in order to buffer the complex signal points until the mean value of the phase offsets for one MCM symbol is determined. The output of the phase rotation unit 524 is applied to the further processing stage 526 for performing the soft-metric calculation.

With respect to the results of the above echo phase offset correction, reference is made again to Figures 3A and 3B. The two plots stem from a simulation which included the first embodiment of an echo phase offset correction algorithm described above. At the instant of the scatter diagram snapshot shown in Figure 3A, the channel obviously distorted the constellation in a way, that a simple angle rotation is a valid assumption. As shown in Figure 3B, the signal constellation can be rotated back to the axis by applying the determined mean value for the rotation of the differentially detected symbols.

A second embodiment of an echo phase offset correction

algorithm is described hereinafter. This second embodiment can be preferably used in connection with multipath channels that have up to two strong path echoes. The algorithm of the second embodiment is more complex than the algorithm of the first embodiment.

What follows is a mathematical derivation of the second embodiment of a method for echo phase offset correction. The following assumptions can be made in order to ease the explanation of the second embodiment of an EPOC algorithm.

In this embodiment, the guard interval of the MCM signal is assumed to be at least as long as the impulse response h[q], q = 0, 1, ..., Qh-1 of the multipath channel.

At the transmitter every MCM symbol is assembled using frequency axis mapping explained above. The symbol of the reference subcarrier equals 1, i.e. 0 degree phase shift. The optional phase shift PHI equals zero, i.e. the DQPSK signal constellation is not rotated.

Using an equation this can be expressed as

$$a_k = a_{k-1} a_k^{inc} \qquad \text{(Eq.7)}$$

with

k : index k = 1,2,...,K of the active subcarrier;

$a_k^{inc} = e^{j\frac{\pi}{2}m}$: complex phase increment symbol; m=0,1,2,3 is the QPSK symbol number which is derived from Gray encoding pairs of 2 Bits;

$a_0 = 1$: symbol of the reference subcarrier.

At the DFT output of the receiver the decision variables

$$e_k = a_k H_k \qquad \text{(Eq.8)}$$

are obtained with

$$H_k = \sum_{i=0}^{Q_h-1} h[i] \cdot e^{-j\frac{2\pi}{K}ki} \qquad \text{(Eq.9)}$$

being the DFT of the channel impulse response $h[q]$ at position k.

With $|a_k|^2 = 1$ the differential demodulation yields

$$v_k = e_k \cdot e_{k-1}^* = a_k^{inc} H_k H_{k-1}^* \qquad \text{(Eq.10)}$$

For the receiver an additional phase term φ_k is introduced, which shall be used to correct the systematic phase offset caused by the channel. Therefore, the final decision variable at the receiver is

$$v'_k = v_k \cdot e^{j\varphi_k} = a_k^{inc} \cdot e^{j\varphi_k} \cdot H_k \cdot H_{k-1}^* \qquad \text{(Eq.11)}$$

As can be seen from the Equation 11, the useful information a_k^{inc} is weighted with the product $e^{j\varphi_k} \cdot H_k \cdot H^*_{k-1}$ (rotation and effective transfer function of the channel). This product must be real-valued for an error free detection. Considering this, it is best to choose the rotation angle to equal the negative argument of $H_k \cdot H^*_{k-1}$. To derive the desired algorithm for 2-path channels, the nature of $H_k \cdot H^*_{k-1}$ is investigated in the next section.

It is assumed that the 2-path channel exhibits two echoes with energy content unequal zero, i.e. at least two dominant echoes. This assumption yields the impulse response

$$h[q] = c_1\delta_0[q] + c_2\delta_0[q - q_0] \qquad \text{(Eq.12)}$$

with

c_1, c_2 : complex coefficients representing the path echoes;

q_0 : delay of the second path echo with respect to the first path echo;

δ_0 : Dirac pulse; $\delta_0[k] = 1$ for $k = 0$
$\delta_0[k] = 0$ else

The channel transfer function is obtained by applying a DFT (Eq.9) to Equation 12:

$$H_k = H\left(e^{j\frac{2\pi}{K}k}\right) = c_1 + c_2 \cdot e^{-j\frac{2\pi}{K}kq_0} \qquad \text{(Eq.13)}$$

With Equation 13 the effective transfer function for differential demodulation along the frequency axis is:

$$\begin{aligned} H_k \cdot H_{k-1}^* &= \left(c_1 + c_2 e^{-j\frac{2\pi}{K}kq_0}\right) \cdot \left(c_1^* + c_2^* e^{+j\frac{2\pi}{K}(k-1)q_0}\right) \\ &= c_a + c_b \cos\left(\frac{\pi}{K} q_0 (2k-1)\right) \end{aligned} \qquad \text{(Eq.14)}$$

Assuming a noise free 2-path channel, it can be observed from Equation 14 that the symbols on the receiver side are located on a straight line in case the symbol 1+j0 has been send (see above assumption). This straight line can be characterized by a point

$$c_a = |c_1|^2 + |c_2|^2 \cdot e^{-j\frac{2\pi}{K}q_0} \qquad \text{(Eq.15)}$$

and the vector

$$c_b = 2c_1c_2^* \cdot e^{-j\frac{\pi}{K}q_0} \qquad \text{(Eq.16)}$$

which determines its direction.

With the above assumptions, the following geometric derivation can be performed. A more suitable notation for the geometric derivation of the second embodiment of an EPOC algorithm is obtained if the real part of the complex plane is designated as $x = \mathrm{Re}\{z\}$, the imaginary part as $y = \mathrm{Im}\{z\}$, respectively, i.e. $z = x+jy$. With this new notation, the

straight line, on which the received symbols will lie in case of a noise-free two-path channel, is

$$f(x) = a + b \cdot x \qquad \text{(Eq.17)}$$

with

$$a = \mathrm{Im}\{c_a\} - \frac{\mathrm{Re}\{c_a\}}{\mathrm{Re}\{c_b\}} \cdot \mathrm{Im}\{c_b\} \qquad \text{(Eq.18)}$$

and

$$b = -\frac{\mathrm{Im}\{c_a\} - \frac{\mathrm{Re}\{c_a\}}{\mathrm{Re}\{c_b\}} \cdot \mathrm{Im}\{c_b\}}{\mathrm{Re}\{c_a\} - \frac{\mathrm{Im}\{c_a\}}{\mathrm{Im}\{c_b\}} \cdot \mathrm{Re}\{c_b\}} \qquad \text{(Eq.19)}$$

Additional noise will spread the symbols around the straight line given by Equations 17 to 19. In this case Equation 19 is the regression curve for the cluster of symbols.

For the geometric derivation of the second embodiment of an EPOC algorithm, the angle φ_K from Equation 11 is chosen to be a function of the square distance of the considered symbol from the origin:

$$\varphi_K = f_K(|z|^2) \qquad \text{(Eq.20)}$$

Equation 20 shows that the complete signal space is distorted (torsion), however, with the distances from the origin being preserved.

For the derivation of the algorithm of the second embodiment, $f_K(\cdot)$ has to be determined such that all decision variables v'_K (assuming no noise) will come to lie on the real axis:

$$\mathrm{Im}\left\{\left(x+jf(x)\right)\cdot e^{j\varphi_k\left(|z|^2\right)}\right\}=0. \qquad \text{(Eq.21)}$$

Further transformations of Equation 21 lead to a quadratic equation which has to be solved to obtain the solution for φ_k.

In case of a two-path channel, the echo phase offset correction for a given decision variable v_k is

$$v_k' = v_k \cdot e^{j\varphi_k} \qquad \text{(Eq.22)}$$

with

$$\varphi_k = \begin{cases} -atan\left(\dfrac{a+b\sqrt{|v_k|^2(1+b^2)-a^2}}{-ab+\sqrt{|v_k|^2(1+b^2)-a^2}}\right) & \text{for } |v_k|^2 \geq \dfrac{a^2}{1+b^2} \\ atan\left(\dfrac{1}{b}\right) & \text{for } |v_k|^2 < \dfrac{a^2}{1+b^2} \end{cases} \qquad \text{(Eq.23)}$$

From the two possible solutions of the quadratic equation mentioned above, Equation 23 is the one solution that cannot cause an additional phase shift of 180 degrees.

The two plots in Figure 6 show the projection of the EPOC algorithm of the second embodiment for one quadrant of the complex plane. Depicted here is the quadratic grid in the sector $|\arg(z)| \leq \pi/4$ and the straight line $y = f(x) = a+b\cdot x$ with $a = -1.0$ and $b = 0.5$ (dotted line). In case of a noise-free channel, all received symbols will lie on this straight line if 1+j0 was send. The circle shown in the plots determines the boarder line for the two cases of Equation 23. In the left part, Figure 6 shows the situation before the projection, in the right part, Figure 6 shows the situation after applying the projection algorithm. By looking on the left part, one can see, that the straight line now lies on the real axis with 2+j0 being the fix point of the projection. Therefore, it can be concluded that the

echo phase offset correction algorithm according to the second embodiment fulfills the design goal.

Before the second embodiment of an EPOC algorithm can be applied, the approximation line through the received symbols has to be determined, i.e. the parameters a and b must be estimated. For this purpose, it is assumed that the received symbols lie in sector $|\arg(z)| \leq \pi/4$, if 1+j0 was sent. If symbols other than 1+j0 have been sent, a modulo operation can be applied to project all symbols into the desired sector. Proceeding like this prevents the necessity of deciding on the symbols in an early stage and enables averaging over all signal points of one MCM symbol (instead of averaging over only ¼ of all signal points).

For the following computation rule for the EPOC algorithm of the second embodiment, x_i is used to denote the real part of the i-th signal point and y_i for its imaginary part, respectively (i = 1, 2,..., K). Altogether, K values are available for the determination. By choosing the method of least squares, the straight line which has to be determined can be obtained by minimizing

$$(a,b) = \underset{(\tilde{a},\tilde{b})}{argmin} \sum_{i=1}^{K} \left(y_i - \left(\tilde{a} + \tilde{b} \cdot x_i\right)\right)^2 \qquad \text{(Eq.24)}$$

The solution for Equation 24 can be found in the laid open literature. It is

$$b = \frac{\sum_{i=1}^{K} \left(x_i - \overline{x}\right) \cdot y_i}{\sum_{i=1}^{K} \left(x_i - \overline{x}\right)^2}, \quad a = \overline{y} - \overline{x} \cdot b \qquad \text{(Eq.25)}$$

with mean values

$$\overline{x} = \frac{1}{N} \sum_{i=1}^{K} x_i, \quad \overline{y} = \frac{1}{N} \sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

If necessary, an estimation method with higher robustness

can be applied. However, the trade-off will be a much higher computational complexity.

To avoid problems with the range in which the projection is applicable, the determination of the straight line should be separated into two parts. First, the cluster's centers of gravity are moved onto the axes, following, the signal space is distorted. Assuming that a and b are the original parameters of the straight line and α is the rotation angle, $f_{K(.)}$ has to be applied with the transformed parameters

$$b' = \frac{b \cdot \cos(\alpha) - \sin(\alpha)}{\cos(\alpha) + b \cdot \sin(\alpha)}, \qquad a' = a \cdot \left(\cos(\alpha) - b' \cdot \sin(\alpha)\right) \qquad \text{(Eq.27)}$$

Besides the two EPOC algorithms explained above section, different algorithms can be designed that will, however, most likely exhibit a higher degree of computational complexity.

The new mapping method for Multicarrier Modulation schemes presented herein consists in principal of two important aspects. Differential mapping within one MCM symbol along the frequency axis direction and correction of the channel echo related phase offset on the subcarriers at the receiver side. The advantage of this new mapping scheme is its robustness with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

CLAIMS

1. A method of mapping information onto at least two simultaneous carriers (202, 206, 208) having different frequencies in a multi-carrier modulation system, said method comprising the step of:

   controlling respective parameters of said at least two carriers such that said information is differential encoded.

2. The method according to claim 1, wherein said controlled parameters of said at least two carriers (202, 206, 208) are respective phases and/or amplitudes of said at least two carriers.

3. The method according to claim 1 or 2, wherein said step of controlling respective parameters of said at least two carriers (202, 206, 208) comprises the step of controlling respective parameters of at least two carriers which are adjacent in the frequency axis direction.

4. The method according to one of claims 1 to 3, further comprising the step of controlling the parameter of one of said at least two carriers (206) in order to define an absolute parameter reference.

5. The method according to one of claims 1 to 4, comprising the step of mapping information onto at least three simultaneous carriers which are equally spaced in the frequency axis direction.

6. A method of performing a multi-carrier modulation of a bitstream (102) in a digital broadcasting transmitter (100), said method comprising the steps of:

   phase shift keying (220) said bitstream by associating a

respective phase shift to one or more bits of said bit-stream; and

differential phase encoding said phase shifts by controlling the phase of a first carrier based on a phase of a simultaneous second carrier and said phase shift, said first and second carriers having different frequencies.

7. The method according to claim 6, wherein the step of differential phase encoding comprises the steps of:

determining (222) the phase of a first carrier based on a phase of a simultaneous second carrier and said phase shift, said first and second carriers having different frequencies;

associating (232) a complex carrier symbol to each phase shift;

assembling (234) a multi-carrier modulation symbol (200) based on said complex carrier symbols; and

performing an inverse Fourier transform (236).

8. The method according to claim 6 or 7, wherein said second carrier is arranged adjacent to said first carrier in the frequency axis direction.

9. The method according to one of claims 6 to 8, wherein said step of phase shift keying (220) said bitstream comprises the step of performing a quadrature phase shift keying using a Gray mapping.

10. The method according to one of claims 6 to 9, comprising the step of controlling the phase of one carrier in order to define an absolute phase reference.

11. The method according to one of claims 6 to 10, comprising the step of controlling the phases of at least three simultaneous carriers which are equally spaced in the frequency axis direction.

12. A method of de-mapping information based on at least two simultaneous encoded carriers having different frequencies in a multi-carrier demodulation system, said method comprising the step of:

recovering said information by differential decoding (142) of respective parameters of said at least two carriers.

13. The method according to claim 12, wherein said step of differential decoding (142) comprises the step of differential decoding respective phases and/or amplitudes of said at least two carriers.

14. The method according to claim 12 or 13, wherein said step of recovering said information comprises the step of decoding respective parameters of at least two carriers which are adjacent in the frequency axis direction.

15. The method according to one of claims 12 to 14, wherein said step of recovering said information comprises the step of decoding respective parameters of at least three simultaneous carriers which are equally spaced in the frequency axis direction.

16. A method of performing a demodulation of a multi-carrier modulated signal in a digital broadcasting system, said method comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

recovering bits of a bitstream from said phase shifts.

17. The method according to claim 16, wherein said step of differential phase decoding comprises the steps of:

performing a Fourier transform (140) to derive a multi-carrier modulated symbol, said multi-carrier modulated symbol comprising complex carrier symbols; and

recovering (142) respective phase shifts from said complex carrier symbols.

18. The method according to claim 16 or 17, wherein said step of differential phase decoding comprises the step of differential phase decoding based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

19. The method according to one of claims 16 to 18, wherein said step of recovering bits of a bitstream from said phase shift comprises the step of demodulating said phase shifts using a Gray de-mapping.

20. The method according to one of claims 16 to 19, wherein said step of differential phase decoding comprises the step of differential phase decoding based on phase differences between at least three simultaneous carriers which are equally spaced in the frequency axis direction.

21. A method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding (142) phase shifts based on a phase difference between simultaneous carriers having different frequencies;

determining an echo phase offset for each decoded phase shift by eliminating (500) phase shift uncertainties corresponding to codeable phase shifts from said decoded phase shift;

averaging (520) said echo phase offsets in order to generate an averaged offset; and

correcting (524) each decoded phase shift based on said averaged offset.

22. The method according to claim 21, wherein said step of differential phase decoding comprises the step of differential phase decoding phase shifts based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

23. The method according to claim 21 or 22, wherein said step of differential phase decoding comprises the step of differential phase decoding phase shifts based on phase differences between at least three simultaneous carriers which are equally spaced in the frequency axis direction.

24. The method according to one of claims 21 to 23, further comprising a step of comparing (516) an absolute value of a symbol associated with a respective decoded phase shift with a threshold, wherein only phase shifts having associated therewith symbols having an absolute value exceeding said threshold are used in said step of averaging said echo phase offsets.

25. A method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a

phase difference between simultaneous carriers having different frequencies, said phase shifts defining signal points in a complex plane;

pre-rotating said signal points into the sector of said complex plane between -45° and +45°;

determining parameters (a, b) of a straight line approximating the location of said pre-rotated signal points in said complex plane;

determining a phase offset based on said parameters (a, b); and

correcting each decoded phase shift based on said phase offset.

26. The method according to claim 25, wherein said simultaneous carriers are equally spaced in the frequency axis direction.

27. The method according to claim 25 or 26, wherein said step of determining said parameters (a, b) comprises a least squares method for selecting those parameters which minimize the deviations of said pre-rotated signal points from said straight line.

28. The method according to claim 27, wherein said parameters (a, b) are determined as follows:

$$b = \frac{\sum_{i=1}^{K}(x_i - \overline{x}) \cdot y_i}{\sum_{i=1}^{K}(x_i - \overline{x})^2}, \quad a = \overline{y} - \overline{x} \cdot b \qquad \text{(Eq.25)}$$

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{K} x_i, \quad \overline{y} = \frac{1}{N}\sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

wherein x and y designate the coordinates of the signal points in the complex plane,

i is an index from 1 to N, and

K is the number of signal points.

29. The method according to claim 28, wherein said phase offset (φ_k) is determined as follows:

$$\varphi_k = \begin{cases} -atan\left(\dfrac{a+b\sqrt{|v_k|^2(1+b^2)-a^2}}{-ab+\sqrt{|v_k|^2(1+b^2)-a^2}}\right) & \text{for} \quad |v_k|^2 \geq \dfrac{a^2}{1+b^2} \\ atan\left(\dfrac{1}{b}\right) & \text{for} \quad |v_k|^2 < \dfrac{a^2}{1+b^2} \end{cases} \qquad \text{(Eq.23)}$$

wherein v_k is a given decision variable.

30. A mapping device for mapping information onto at least two simultaneous carriers (202, 206, 208) having different frequencies, for a multi-carrier modulation system, said device comprising means for controlling respective parameters of said at least two carriers such that said information is differential encoded.

31. The device according to claim 30, wherein said means for controlling respective parameters of said at least two carriers (202, 206, 208) is adapted to control respective phases and/or amplitudes of said at least two carriers.

32. The device according to claim 30 or 31, wherein said means for controlling respective parameters of said at least two carriers (202, 206, 208) comprises means for controlling respective parameters of at least two carriers which are adjacent in the frequency axis direction.

33. The device according to one of claims 30 to 32, further comprising means for controlling the parameter of one (206) of said at least two carriers such that an absolute parameter reference is defined by said carrier.

34. The device according to one of claims 30 to 33, further comprising means for controlling the parameters of at least three carriers which are equally spaced in the frequency axis direction.

35. A multi-carrier modulator for performing a multi-carrier modulation of a bitstream (102), for a digital broadcasting transmitter (100), said modulator comprising:

means for phase shift keying (220) said bitstream by associating a respective phase shift to one or more bits of said bitstream; and

a differential phase encoder for differential phase encoding said phase shifts by controlling the phase of a first carrier based on a phase of a simultaneous second carrier and said phase shift, said first and second carriers having different frequencies.

36. The modulator according to claim 35, wherein said differential phase encoder comprises:

means (222) for determining the phase of a first carrier based on a phase of a simultaneous second carrier and said phase shift, said first and second carriers having different frequencies;

means (232) for associating a complex carrier symbol to each phase shift;

means (234) for assembling a multi-carrier modulation symbol based on said complex carrier symbols; and

means (236) for performing an inverse Fourier transform.

37. The modulator according to claim 35 or 36, wherein said means (222) for determining said phase of said first carrier is adapted to determine said phase based on a phase of a simultaneous second carrier which is arranged adjacent to said first carrier in the frequency axis direction and said phase shift.

38. The modulator according to one of claims 35 to 37, wherein said means (220) for phase shift keying said bitstream comprises means for performing a quadrature phase shift keying using a Gray mapping.

39. The modulator according to one of claims 35 to 38, comprising means for controlling the phase of one carrier in order to define an absolute phase reference.

40. The modulator according to one of claims 35 to 39, comprising means for controlling the phases of at least three carriers which are equally spaced in the frequency axis direction.

41. A de-mapping device for de-mapping information based on at least two simultaneous encoded carriers having different frequencies, for a multi-carrier demodulation system (130), said de-mapping device (142) comprising:

means for recovering said information by differential decoding of respective parameters of said at least two carriers.

42. The device according to claim 41, wherein said means for recovering said information is adapted to differential decode respective phases and/or amplitudes of said at least two carriers.

43. The device according to claim 41 or 42, wherein said

means for recovering said information comprises means for decoding respective parameters of at least two carriers which are adjacent in the frequency axis direction.

44. The device according to one of claims 41 to 43, wherein said means for recovering said information comprises means for decoding respective parameters of at least three simultaneous carriers which are equally spaced in the frequency axis direction.

45. A demodulator for demodulating a multi-carrier modulated signal, for a digital broadcasting system, said demodulator comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for recovering bits of a bitstream from said phase shifts.

46. The demodulator according to claim 45, wherein said differential phase decoder comprises:

means (140) for performing a Fourier transform to derive a multi-carrier modulated symbol, said multi-carrier modulated symbol comprising complex carrier symbols; and

means (142) for recovering respective phase shifts from said complex carrier symbols.

47. The demodulator according to claim 45 or 46, wherein said differential phase decoder is adapted for decoding phase shifts based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

48. The demodulator according to one of claims 45 to 47, wherein said means for recovering bits of a bitstream from said phase shift comprises a Gray de-mapper.

49. The demodulator according to one of claims 45 to 48, wherein said simultaneous carriers are equally space in the frequency axis direction.

50. An echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder (142) for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for determining an echo phase offset for each decoded phase shift comprising means (500) for eliminating phase shift uncertainties corresponding to codeable phase shifts from said decoded phase shift;

means (520) for averaging said echo phase offsets in order to generate an averaged offset; and

means (524) for correcting each decoded phase shift based on said averaged offset.

51. The device according to claim 50, wherein said differential phase decoder is adapted for decoding said phase shifts based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

52. The device according to claim 50 or 51, further comprising means (516) for comparing an absolute value of a symbol associated with a respective decoded phase shift with a threshold, wherein said means for averaging said phase offsets only uses phase shifts having associated therewith symbols having an absolute value

exceeding said threshold.

53. The device according to one of claims 50 to 52, wherein said differential phase decoder is adapted for decoding said phase shifts based on phase differences between at least three simultaneous carriers which are equally spaced in the frequency axis direction.

54. An echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, said phase shifts defining signal points in a complex plane;

means for pre-rotating said signal points into the sector of said complex plane between -45° and +45°;

means for determining parameters (a, b) of a straight line approximating the location of said pre-rotated signal points in said complex plane;

means for determining a phase offset based on said parameters (a, b); and

means for correcting each decoded phase shift based on said phase offset.

55. The device according to claim 54, wherein said differential phase decoder comprises means for decoding phase shifts of at least three simultaneous carriers which are equally spaced in the frequency axis direction.

56. The device according to claim 54 or 55, wherein said means for determining said parameters (a, b) comprises means for performing a least squares method for

selecting those parameters which minimize the deviations of said pre-rotated signal points from said straight line.

57. The device according to claim 56, wherein said means for determining said parameters (a, b) calculates said parameters (a, b) as follows:

$$b = \frac{\sum_{i=1}^{K}\left(x_i - \overline{x}\right)\cdot y_i}{\sum_{i=1}^{K}\left(x_i - \overline{x}\right)^2}, \quad a = \overline{y} - \overline{x}\cdot b \qquad \text{(Eq.25)}$$

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{K} x_i, \quad \overline{y} = \frac{1}{N}\sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

wherein x and y designate the coordinates of the signal points in the complex plane,

i is an index from 1 to N, and

K is the number of signal points.

58. The device according to claim 57, wherein said means for determining said phase offset (φ_k) calculates said phase offset (φ_k) as follows:

$$\varphi_k = \begin{cases} -atan\left(\dfrac{a + b\sqrt{|v_k|^2\left(1+b^2\right) - a^2}}{-ab + \sqrt{|v_k|^2\left(1+b^2\right) - a^2}}\right) & \text{for } |v_k|^2 \geq \dfrac{a^2}{1+b^2} \\ atan\left(\dfrac{1}{b}\right) & \text{for } |v_k|^2 < \dfrac{a^2}{1+b^2} \end{cases} \qquad \text{(Eq.23)}$$

wherein v_k is a given decision variable.

METHOD AND APPARATUS FOR MULTI-CARRIER MODULATION AND DE-MODULATION AND METHOD AND APPARATUS FOR PERFORMING AN ECHO PHASE OFFSET CORRECTION ASSOCIATED THEREWITH

ABSTRACT

A method of mapping information onto at least two simultaneous carriers (202, 206, 208) having different frequencies in a multi-carrier modulation system involves the step of controlling respective parameters of the at least two carriers such that the information is differential encoded. A method of de-mapping information based on at least two simultaneous encoded carriers having different frequencies in a multi-carrier demodulation system comprises the step of recovering the information by differential decoding (142) of respective parameters of the at least two carriers. In a method of performing an echo phase offset correction in a multi-carrier demodulation system, phase shifts are differential phase decoded (142) based on a phase difference between simultaneous carriers having different frequencies. An echo phase offset is determined for each decoded phase shift by eliminating (500) phase shift uncertainties corresponding to codeable phase shifts from the decoded phase shift. The echo phase offsets are averaged (520) in order to generate an averaged offset. Finally, each decoded phase shift is corrected (524) based on the averaged offset.

09/673266

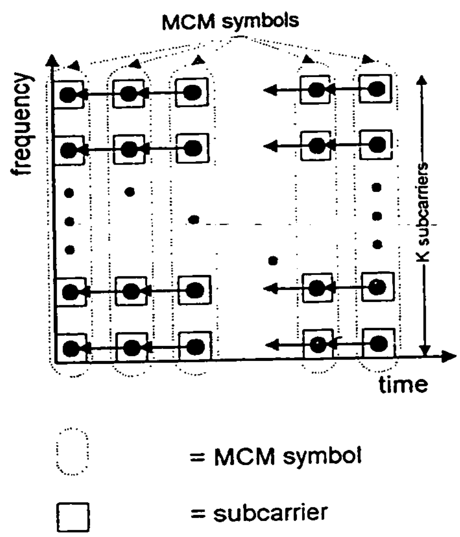


Fig. 8

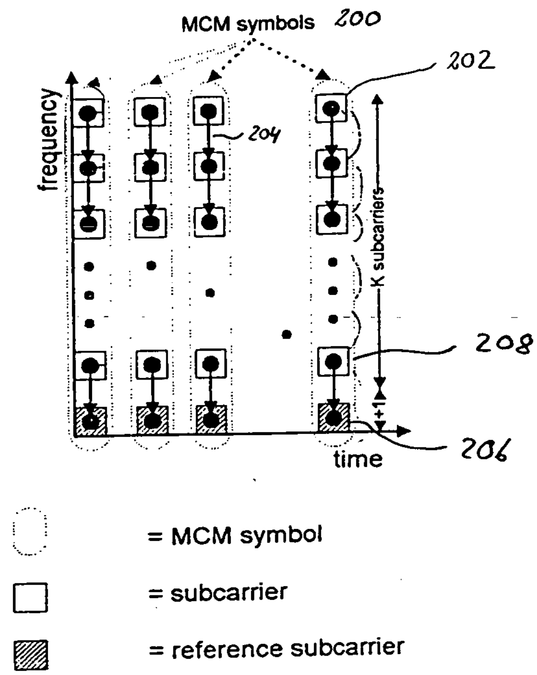


Fig. 1

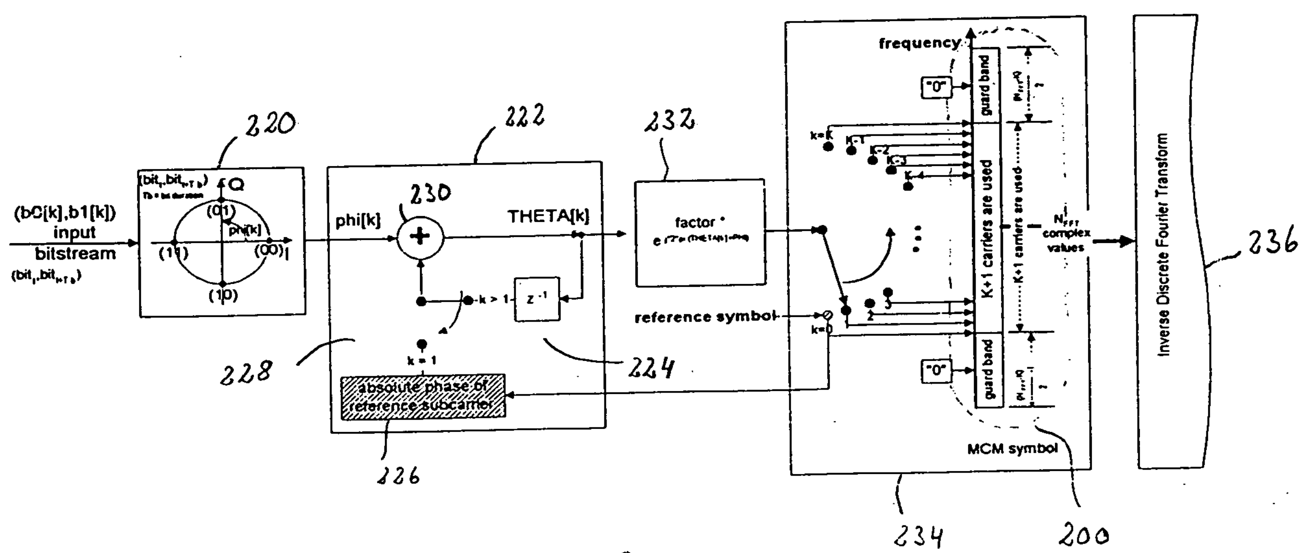


Fig. 2

09/673266

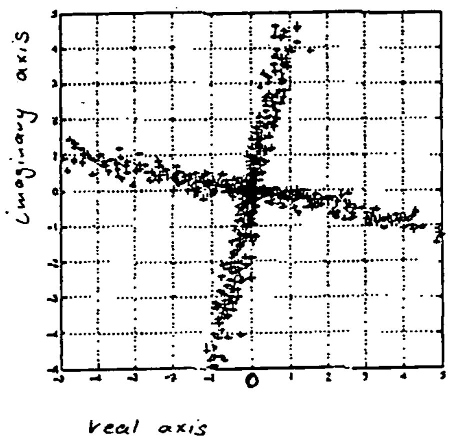


Fig. 3A

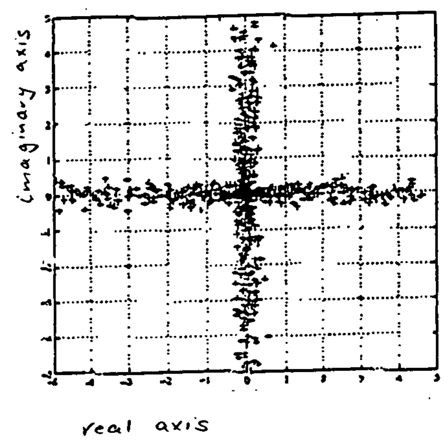


Fig. 3B

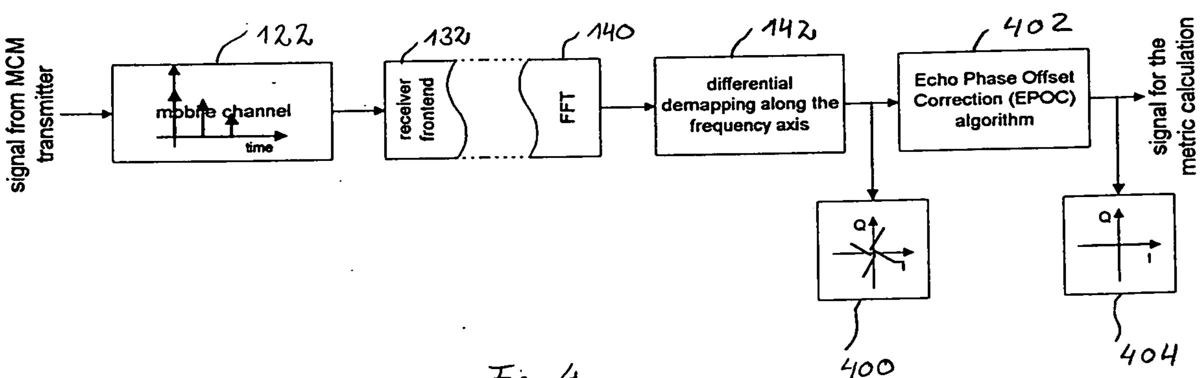
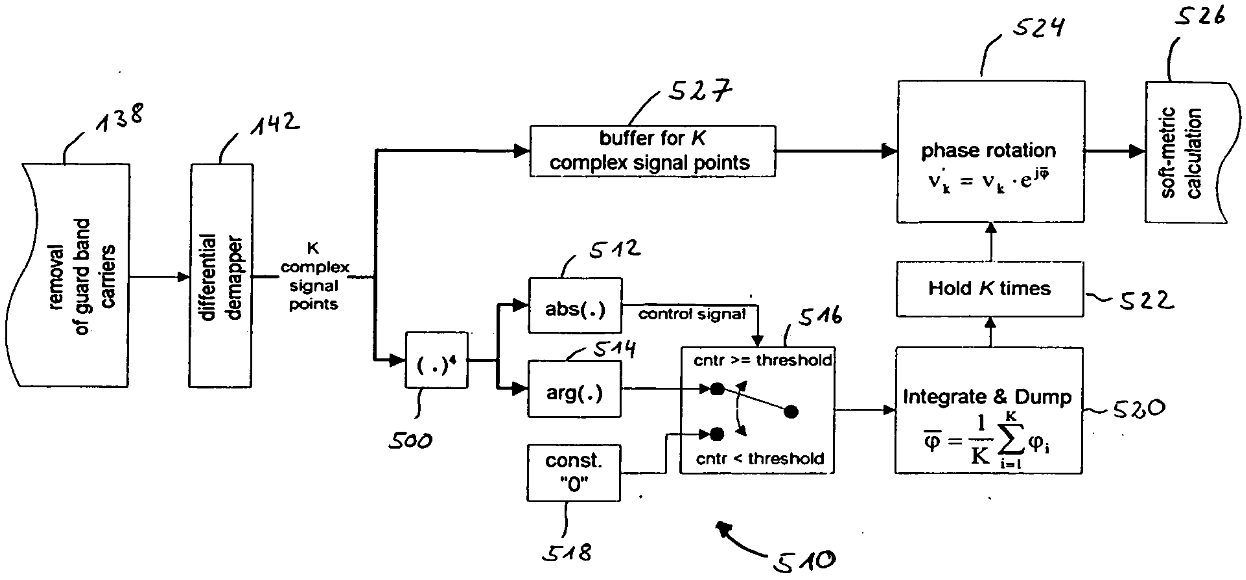
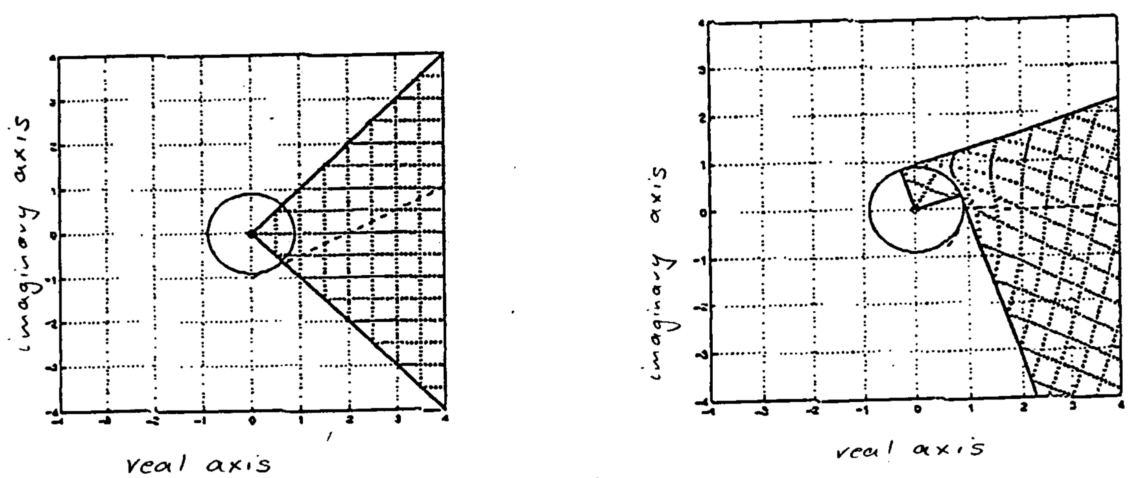


Fig. 4



138
removal of guard band carriers
142
differential demapper
K complex signal points
527
buffer for K complex signal points
524
phase rotation
$v_k' = v_k \cdot e^{j\bar{\varphi}}$
526
soft-metric calculation
512
abs(.)
control signal
516
514
arg(.)
(.)⁴
500
cntr >= threshold
cntr < threshold
const. "0"
518
510
Hold K times
522
Integrate & Dump
$\bar{\varphi} = \frac{1}{K}\sum_{i=1}^{K}\varphi_i$
520

Fig. 5



imaginary axis
real axis
imaginary axis
real axis

Fig. 6

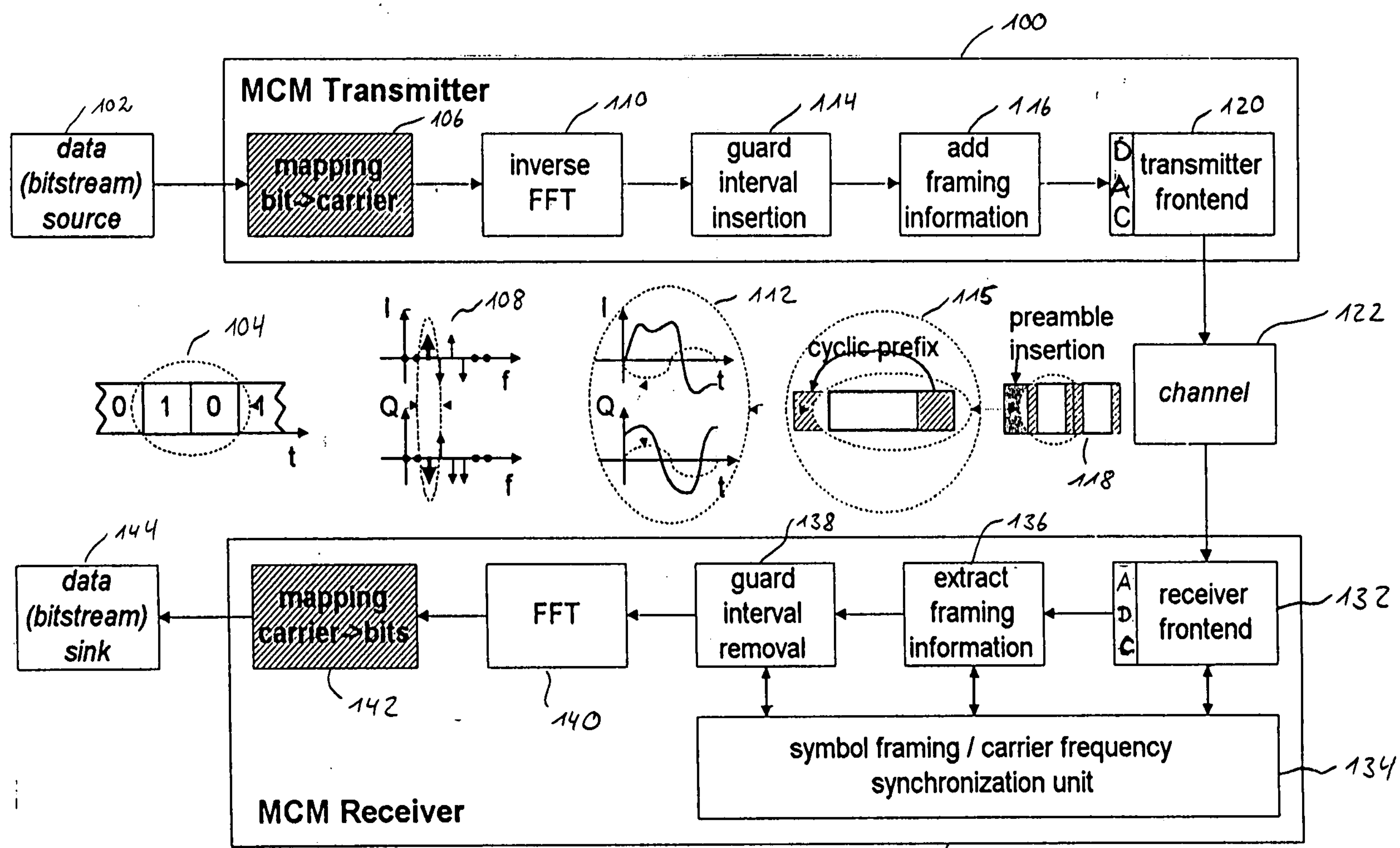

100
MCM Transmitter
102
data (bitstream) source
106
mapping bit->carrier
110
inverse FFT
114
guard interval insertion
116
add framing information
120
D A C
transmitter frontend
122
channel
104
0 1 0 1
t
108
I
Q
f
112
t
115
cyclic prefix
preamble insertion
118
144
data (bitstream) sink
mapping carrier->bits
142
FFT
140
138
guard interval removal
136
extract framing information
A D C
receiver frontend
132
symbol framing / carrier frequency synchronization unit
134
MCM Receiver
130

Fig. 7

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To:
SCHOPPE & ZIMMERMANN
Postfach 71 08 67
D-81458 München
GERMANY

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT OR THE DECLARATION

(PCT Rule 44.1)

	Date of mailing (*day/month/year*) 12/01/1999
Applicant's or agent's file reference FH980405PCT	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/EP 98/02167	International filing date (*day/month/year*) 14/04/1998
Applicant FRAUNHOFER-GESELLSCHAFT ZUR FÖRDERUNG .... et al.	

1. [X] The applicant is hereby notified that the International Search Report has been established and is transmitted herewith.

Filing of amendments and statement under Article 19:
The applicant is entitled, if he so wishes, to amend the claims of the International Application (see Rule 46):

When? The time limit for filing such amendments is normally 2 months from the date of transmittal of the International Search Report; however, for more details, see the notes on the accompanying sheet.

Where? Directly to the International Bureau of WIPO
34, chemin des Colombettes
1211 Geneva 20, Switzerland
Fascimile No.: (41-22) 740.14.35

For more detailed instructions, see the notes on the accompanying sheet.

2. [ ] The applicant is hereby notified that no International Search Report will be established and that the declaration under Article 17(2)(a) to that effect is transmitted herewith.

3. [ ] **With regard to the protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

[ ] the protest together with the decision thereon has been transmitted to the International Bureau together with the applicants's request to forward the texts of both the protest and the decision thereon to the designated Offices.

[ ] no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Further action(s):** The applicant is reminded of the following:

Shortly after **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau as provided in Rules 90*bis*.1 and 90*bis*.3, respectively, before the completion of the technical preparations for international publication.

Within **19 months** from the priority date, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase until 30 months from the priority date (in some Offices even later).

Within **20 months** from the priority date, the applicant must perform the prescribed acts for entry into the national phase before all designated Offices which have not been elected in the demand or in a later election within 19 months from the priority date or could not be elected because they are not bound by Chapter II.

Name and mailing address of the International Searching Authority	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	René Stolk

NOTES TO FORM PCT/ISA/220

These Notes are intended to give the basic instructions concerning the filing of amendments under article 19. The Notes are based on the requirements of the Patent Cooperation Treaty, the Regulations and the Administrative Instructions under that Treaty. In case of discrepancy between these Notes and those requirements, the latter are applicable. For more detailed information, see also the PCT Applicant's Guide, a publication of WIPO.

In these Notes, "Article", "Rule", and "Section" refer to the provisions of the PCT, the PCT Regulations and the PCT Administrative Instructions respectively.

INSTRUCTIONS CONCERNING AMENDMENTS UNDER ARTICLE 19

The applicant has, after having received the international search report, one opportunity to amend the claims of the international application. It should however be emphasized that, since all parts of the international application (claims, description and drawings) may be amended during the international preliminary examination procedure, there is usually no need to file amendments of the claims under Article 19 except where, e.g. the applicant wants the latter to be published for the purposes of provisional protection or has another reason for amending the claims before international pbulication. Furthermore, it should be emphasized that provisional protection is available in some States only.

What parts of the international application may be amended?

Under Article 19, only the claims may be amended.

During the international phase, the claims may also be amended (or further amended) under Article 34 before the International Preliminary Examining Authority. The description and drawings may only be amended under Article 34 before the International Examining Authority.

Upon entry into the national phase, all parts of the international application may be amended under Article 28 or, where applicable, Article 41.

When? Within 2 months from the date of transmittal of the international search report or 16 months from the priority date, whichever time limit expires later. It should be noted, however, that the amendments will be considered as having been received on time if they are received by the International Bureau after the expiration of the applicable time limit but before the completion of the technical preparations for international publication (Rule 46.1).

Where not to file the amendments?

The amendments may only be filed with the International Bureau and not with the receiving Office or the International Searching Authority (Rule 46.2).

Where a demand for international preliminary examination has been/is filed, see below.

How? Either by cancelling one or more entire claims, by adding one or more new claims or by amending the text of one or more of the claims as filed.

A replacement sheet must be submitted for each sheet of the claims which, on account of an amendment or amendments, differs from the sheet originally filed.

All the claims appearing on a replacement sheet must be numbered in Arabic numerals. Where a claim is cancelled, no renumbering of the other claims is required. In all cases where claims are renumbered, they must be renumbered consecutively (Administrative Instructions, Section 205(b)).

The amendments must be made in the language in which the international application is to be published.

What documents must/may accompany the amendments?

Letter (Section 205(b)):

The amendments must be submitted with a letter.

The letter will not be published with the international application and the amended claims. It should not be confused with the "Statement under Article 19(1)" (see below, under "Statement under Article 19(1)").

The letter must be in English or French, at the choice of the applicant. However, if the language of the international application is English, the letter must be in English; if the language of the international application is French, the letter must be in French.

The letter must indicate the differences between the claims as filed and the claims as amended. It must, in particular, indicate, in connection with each claim appearing in the international application (it being understood that identical indications concerning several claims may be grouped), whether

(i) the claim is unchanged;

(ii) the claim is cancelled;

(iii) the claim is new;

(iv) the claim replaces one or more claims as filed;

(v) the claim is the result of the division of a claim as filed.

The following examples illustrate the manner in which amendments must be explained in the accompanying letter:

1. [Where originally there were 48 claims and after amendment of some claims there are 51]: "Claims 1 to 29, 31, 32, 34, 35, 37 to 48 replaced by amended claims bearing the same numbers; claims 30, 33 and 36 unchanged; new claims 49 to 51 added."

2. [Where originally there were 15 claims and after amendment of all claims there are 11]: "Claims 1 to 15 replaced by amended claims 1 to 11."

3. [Where originally there were 14 claims and the amendments consist in cancelling some claims and in adding new claims]:
"Claims 1 to 6 and 14 unchanged; claims 7 to 13 cancelled; new claims 15, 16 and 17 added." or
"Claims 7 to 13 cancelled; new claims 15, 16 and 17 added; all other claims unchanged."

4. [Where various kinds of amendments are made]:
"Claims 1-10 unchanged; claims 11 to 13, 18 and 19 cancelled; claims 14, 15 and 16 replaced by amended claim 14; claim 17 subdivided into amended claims 15, 16 and 17; new claims 20 and 21 added."

"Statement under article 19(1)" (Rule 46.4)

The amendments may be accompanied by a statement explaining the amendments and indicating any impact that such amendments might have on the description and the drawings (which cannot be amended under Article 19(1)).

The statement will be published with the international application and the amended claims.

It must be in the language in which the international appplication is to be published.

It must be brief, not exceeding 500 words if in English or if translated into English.

It should not be confused with and does not replace the letter indicating the differences between the claims as filed and as amended. It must be filed on a separate sheet and must be identified as such by a heading, preferably by using the words "Statement under Article 19(1)."

It may not contain any disparaging comments on the international search report or the relevance of citations contained in that report. Reference to citations, relevant to a given claim, contained in the international search report may be made only in connection with an amendment of that claim.

Consequence if a demand for international preliminary examination has already been filed

If, at the time of filing any amendments under Article 19, a demand for international preliminary examination has already been submitted, the applicant must preferably, at the same time of filing the amendments with the International Bureau, also file a copy of such amendments with the International Preliminary Examining Authority (see Rule 62.2(a), first sentence).

Consequence with regard to translation of the international application for entry into the national phase

The applicant's attention is drawn to the fact that, where upon entry into the national phase, a translation of the claims as amended under Article 19 may have to be furnished to the designated/elected Offices, instead of, or in addition to, the translation of the claims as filed.

For further details on the requirements of each designated/elected Office, see Volume II of the PCT Applicant's Guide.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 98/02167

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04L27/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MOOSE: "Differentially coded multi-frequency modulation for digital communications" SIGNAL PROCESSING THEORIES AND APPLICATIONS, 18 - 21 September 1990, pages 1807-1810, XP000365916 Amsterdam, NL see page 1807, left-hand column, paragraph 1 see page 1808, right-hand column, paragraph 4 ---	1-24, 30-49
A	WO 92 05646 A (NATIONAL TRANSCOMMUNICATIONS) 2 April 1992 see page 9, line 1 - line 14 ---	25-29, 50-58
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
5 January 1999	12/01/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Scriven, P

1

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 98 00946 A (LELAND STANFORD JUNIOR UNIVERSITY) 8 January 1998 see abstract; figure 15 ---	25,26, 50,51,53
A	MOOSE: "A technique for orthogonal frequency division multiplexing frequency offset correction" IEEE TRANSACTIONS ON COMMUNICATIONS., vol. 42, no. 10, October 1994, pages 2908-2914, XP002019915 NEW YORK, US cited in the application see page 2910, right-hand column, paragraph 1 - page 2911, right-hand column, paragraph 4 ---	25,26, 50,51,53
A	KELLER; HANZO: "Orthogonal frequency division muliplex synchronisation techniques for wireless local area networks" IEEE INTERNATIONAL SYMPOSIUM ON PERSONAL, INDOOR AND MOBILE RADIO COMMUNICATIONS, 15 October 1996, pages 963-967, XP002063294 New York, US see page 965, right-hand column, paragraph 3 - page 967, left-hand column, paragraph 4 -----	25,26, 50,51,53

1

INTERNATIONAL SEARCH REPORT

Inf[redacted]n on patent family members

In[redacted]ional Application No
[redacted]EP 98/02167

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9205646 A	02-04-1992	AT 139660 T	15-07-1996
		AT 160475 T	15-12-1997
		AU 651818 B	04-08-1994
		AU 7584591 A	30-10-1991
		AU 646298 B	17-02-1994
		AU 8613691 A	15-04-1992
		CA 2078445 A	01-10-1991
		CA 2085728 A	15-03-1992
		DE 69120401 D	25-07-1996
		DE 69120401 T	02-01-1997
		DE 69128252 D	02-01-1998
		DE 69128252 T	20-05-1998
		EP 0521995 A	13-01-1993
		EP 0548205 A	30-06-1993
		FI 924373 A	29-09-1992
		FI 931017 A	08-03-1993
		WO 9115925 A	17-10-1991
		JP 5505290 T	05-08-1993
		JP 6501357 T	10-02-1994
		NO 180789 B	10-03-1997
		US 5345440 A	06-09-1994
		US 5488632 A	30-01-1996
WO 9800946 A	08-01-1998	US 5732113 A	24-03-1998

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference FH980405PCT	**FOR FURTHER ACTION** see Notification of Transmittal of International Search Report (Form PCT/ISA/220) as well as, where applicable, item 5 below.	
International application No. PCT/EP 98/ 02167	International filing date *(day/month/year)* 14/04/1998	(Earliest) Priority Date *(day/month/year)*
Applicant FRAUNHOFER-GESELLSCHAFT ZUR FÖRDERUNG .... et al.		

This International Search Report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This International Search Report consists of a total of 3 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. [ ] **Certain claims were found unsearchable** (see Box I).

2. [ ] **Unity of invention is lacking** (see Box II).

3. [ ] The international application contains disclosure of a **nucleotide and/or amino acid sequence listing** and the international search was carried out on the basis of the sequence listing
   - [ ] filed with the international application.
   - [ ] furnished by the applicant separately from the international application,
     - [ ] but not accompanied by a statement to the effect that it did not include matter going beyond the disclosure in the international application as filed.
   - [ ] Transcribed by this Authority

4. With regard to the **title**,
   - [ ] the text is approved as submitted by the applicant
   - [X] the text has been established by this Authority to read as follows:

DIFFERENTIAL CODING AND CARRIER RECOVERY FOR MULTICARRIER SYSTEMS

5. With regard to the **abstract**,
   - [X] the text is approved as submitted by the applicant
   - [ ] the text has been established, according to Rule 38.2(b), by this Authority as it appears in Box III. The applicant may, within one month from the date of mailing of this International Search Report, submit comments to this Authority.

6. The figure of the **drawings** to be published with the abstract is:

   Figure No. 1
   - [X] as suggested by the applicant.
   - [ ] because the applicant failed to suggest a figure.
   - [ ] because this figure better characterizes the invention.
   - [ ] None of the figures.

PCT

REQUEST

The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty.

For receiving Office use only
International Application No.
International Filing Date
Name of receiving Office and "PCT International Application"

Applicant's or agent's file reference *(if desired) (12 characters maximum)* FH980405PCT

Box No. I TITLE OF INVENTION

METHOD AND APPARATUS FOR MULTI-CARRIER MODULATION AND DE-MODULATION AND METHOD AND APPARATUS FOR PERFORMING AN ECHO PHASE OFFSET CORRECTION ASSOCIATED THEREWITH

Box No. II APPLICANT

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 98/02167

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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527 Rec'd PCT/PT 29 NOV 2000

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PATENT

#3

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

OIPE NOV 29 2000 JC99 PATENT & TRADEMARK OFFICE

In re Application of:	:	
Ernst Eberlein et al.	:	Group Art Unit:
Serial No.: 09/673,266	:	Examiner:
Filed: October 13, 2000	:	
For: Echo Phase Offset Correction in a Multi-Carrier Demodulation System (As Amended)	:	

TRANSMITTAL OF DECLARATION

Commissioner for Patents
Washington, D.C. 20231

Sir:

In response to the "Notification of Missing Requirements Under 35 U.S.C. 371 in the United States Designated/Elected Office (DO/EO/US)" mailed on November 13, 2000, the undersigned attorney herewith transmits three (3) declarations under 37 C.F.R. 1.63 executed by the inventors herein. The surcharge under 37 C.F.R. 1.492(e) was paid on October 13, 2000, simultaneously with the national stage entry under 35 U.S.C. 371, and hence is not being submitted herewith. However, the Office is authorized to charge any deficiency or credit any overpayment to Deposit Account number 18-2220.

Respectfully submitted,

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Dated: November 29, 2000

symbols adjacent in time. If this requirement is not met, the channel induced phase and amplitude changes between MCM symbols will yield an increase in bit error rate.

With non-differential mapping exact knowledge of the phase of each subcarrier is needed (i.e. coherent reception). For multipath channels, coherent reception can only be obtained if the channel impulse response is known. Therefore, a channel estimation has to be part of the receiver algorithm. The channel estimation usually needs additional sequences in the transmitted waveform which do not carry information. In case of rapidly changing channels, which necessitate update of the channel estimation at short intervals, the additional overhead can quickly lead to insufficiency of non-differential mapping.

P.H. Moose: "Differentially Coded Multi-Frequency Modulation for Digital Communications", SIGNAL PROCESSING THEORIES AND APPLICATIONS, 18. - 21. September 1990, pages 1807 - 1810, Amsterdam, NL, teaches a differentially coded multi-frequency modulation for digital communications. A multi-frequency differential modulation is described in which symbols are differentially encoded within each baud between adjacent tones. At the receiver, following a digital Fourier transform (DFT), the complex product between the DFT coefficient of digital frequency k and the complex conjugate of the DFT coefficient of digital frequency k-1 is formed. Thereafter, the result is multiplied by appropriate terms such that the differentially encoded phase bits are realigned to the original constellations. Thus, the constellation following the differential decoding must correspond to the original constellation.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide methods and devices for performing an echo phase offset correction in a multi-carrier demodulation system.

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This object is achieved by methods according to claims 1 and 5 and devices according to claims 10 and 14.

In accordance with a first aspect, the present invention provides a method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties related to the transmitted information from the decoded phase shift;

averaging the echo phase offsets in order to generate an averaged offset; and

correcting each decoded phase shift based on the averaged offset.

In accordance with a second aspect, the present invention provides a method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

determining parameters of a straight line approximating the location of the pre-rotated signal points in the

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complex plane;

determining a phase offset based on the parameters; and

correcting each decoded phase shift based on the phase offset.

In accordance with an third aspect, the present invention provides an echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties related to the transmitted information from the decoded phase shift;

means for averaging the echo phase offsets in order to generate an averaged offset; and

means for correcting each decoded phase shift based on the averaged offset.

In accordance with a fourth aspect, the present invention provides an echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

means for pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

means for determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

means for determining a phase offset based on the parameters; and

means for correcting each decoded phase shift based on the phase offset.

The present invention provides methods and devices for performing an echo phase offset correction suitable for multicarrier (OFDM) digital broadcasting over rapidly changing multipath channels, using differential encoding of the data along the frequency axis such that there is no need for channel stationarity exceeding one multicarrier symbol.

When using the mapping process along the frequency axis it is preferred to make use of a receiver algorithm that will correct symbol phase offsets that can be caused by channel echoes.

The mapping scheme along the frequency axis for multi-carrier modulation renders the transmission to a certain extent independent of rapid changes in the multipath channel without introducing a large overhead to support channel estimation. Especially systems with high carrier frequencies and/or high speeds of the mobile carrying the receiving unit can benefit from such a mapping scheme.

Thus, the mapping scheme of a differential encoding along the frequency axis does not exhibit the two problems of the prior art systems described above. The mapping scheme is robust with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

The controlled respective parameters of the subcarriers are

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the phases thereof, such that the information is differentially phase encoded.

In accordance with the mapping described above, mapping is also differential, however, not into time axis direction but into frequency axis direction. Thus, the information is not contained in the phase shift between subcarriers adjacent in time but in the phase shift between subcarriers adjacent in frequency. Differential mapping along the frequency axis has two advantages when compared to other mapping schemes. Because of differential mapping, no estimation of the absolute phase of the subcarriers is required. Therefore, channel estimation and the related overhead are not necessary. By choosing the frequency axis as direction for differentially encoding the information bitstream, the requirement that the channel must be stationary during several MCM symbols can be dropped. The channel only has to remain unchanged during the current MCM symbol period. Therefore, like for non-differential mapping it holds that

required channel coherence time $\geq$ MCM symbol period.

The present invention provides methods and apparatus for correction of phase distortions that can be caused by channel echoes. As described above, differential mapping into frequency axis direction solves problems related to the stationarity of the channel. However, differential mapping into frequency axis direction may create a new problem. In multipath environments, path echoes succeeding or preceding the main path can lead to systematic phase offsets between subcarriers in the same MCM symbol. In this context, the main path is thought of being the path echo with the highest energy content. The main path echo will determine the position of the FFT window in the receiver of an MCM system.

According to the present invention, the information will be contained in a phase shift between adjacent subcarriers of the same MCM symbol. If not corrected for, the path echo

induced phase offset between two subcarriers can lead to an increase in bit error rate. Therefore, application of the MCM mapping scheme presented in this invention will preferably be used in combination with a correction of the systematic subcarrier phase offsets in case of a multipath channel.

The introduced phase offset can be explained from the shifting property of the Discrete Fourier Transform (DFT):

$$x\left[((n-m))_N\right] \xleftrightarrow{DFT} X[k]e^{-j\frac{2\pi}{N}km} \qquad \text{(Eq.3)}$$

with $x[n]$: sampled time domain signal ($0 \le n \le N-1$)

$X[k]$: DFT transformed frequency domain signal ($0 \le k \le N-1$)

N : length of DFT

$(...)_N$: cyclic shift of the DFT window in the time

m : length of DFT-Shift in the time domain

Equation 3 shows, that in a multipath channel, echoes following the main path will yield a subcarrier dependent phase offset. After differential demapping in the frequency axis direction at the receiver, a phase offset between two neighboring symbols remains. Because the channel induced phase offsets between differentially demodulated symbols are systematic errors, they can be corrected by an algorithm.

In the context of the following specification, algorithms which help correcting the phase shift are called Echo Phase Offset Correction (EPOC) algorithms. Two such algorithms are described as preferred embodiments for the correction of phase distortions that can be caused by channel echoes. These algorithms yield a sufficient detection security for MCM frequency axis mapping even in channels with echoes close to the limits of the guard interval.

In principle, an EPOC algorithm must calculate the echo induced phase offset from the signal space constellation

following the differential demodulation and subsequently correct this phase offset.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following, preferred embodiments of the present invention will be explained in detail on the basis of the drawings enclosed, in which:

Figure 1 shows a schematic view representing a mapping scheme used according to the invention;

Figure 2 shows a functional block diagram of an embodiment of a mapping device;

Figures 3A and 3B show scatter diagrams of the output of an differential de-mapper of a MCM receiver for illustrating the effect of an echo phase offset correction;

Figure 4 shows a schematic block diagram for illustrating the position and the functionality of an echo phase offset correction unit;

Figure 5 shows a schematic block diagram of an embodiment of an echo phase offset correction device according to the present invention;

Figure 6 shows schematic views for illustrating a projection performed by another embodiment of an echo phase offset correction device according to the present invention;

Figure 7 shows a schematic block diagram of a generic multi-carrier modulation system; and

Figure 8 shows a schematic view representing a prior art

differential mapping scheme.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In a preferred embodiment thereof, the present invention is applied to a MCM system as shown in Figure 7. With respect

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NEW CLAIMS

1. A method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

   differential phase decoding (142) phase shifts based on a phase difference between simultaneous carriers having different frequencies;

   determining an echo phase offset for each decoded phase shift by eliminating (500) phase shift uncertainties related to the transmitted information from said decoded phase shift;

   averaging (520) said echo phase offsets in order to generate an averaged offset; and

   correcting (524) each decoded phase shift based on said averaged offset.

2. The method according to claim 1, wherein said step of differential phase decoding comprises the step of differential phase decoding phase shifts based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

3. The method according to claim 1 or 2, wherein said step of differential phase decoding comprises the step of differential phase decoding phase shifts based on phase differences between at least three simultaneous carriers which are equally spaced in the frequency axis direction.

4. The method according to one of claims 1 to 3, further comprising a step of comparing (516) an absolute value of a symbol associated with a respective decoded phase shift with a threshold, wherein only phase shifts having

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associated therewith symbols having an absolute value exceeding said threshold are used in said step of averaging said echo phase offsets.

5. A method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, said phase shifts defining signal points in a complex plane;

pre-rotating said signal points into the sector of said complex plane between -45° and +45°;

determining parameters (a, b) of a straight line approximating the location of said pre-rotated signal points in said complex plane;

determining a phase offset based on said parameters (a, b); and

correcting each decoded phase shift based on said phase offset.

6. The method according to claim 5, wherein said simultaneous carriers are equally spaced in the frequency axis direction.

7. The method according to claim 5 or 6, wherein said step of determining said parameters (a, b) comprises a least squares method for selecting those parameters which minimize the deviations of said pre-rotated signal points from said straight line.

8. The method according to claim 7, wherein said parameters (a, b) are determined as follows:

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$$b = \frac{\sum_{i=1}^{K}(x_i - \bar{x}) \cdot y_i}{\sum_{i=1}^{K}(x_i - \bar{x})^2}, \quad a = \bar{y} - \bar{x} \cdot b \qquad \text{(Eq.25)}$$

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{K} x_i, \quad \bar{y} = \frac{1}{N}\sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

wherein x and y designate the coordinates of the signal points in the complex plane,

i is an index from 1 to N, and

K is the number of signal points.

9. The method according to claim 8, wherein said phase offset (φ_k) is determined as follows:

$$\varphi_k = \begin{cases} -atan\left(\dfrac{a + b\sqrt{|v_k|^2(1+b^2) - a^2}}{-ab + \sqrt{|v_k|^2(1+b^2) - a^2}}\right) & \text{for } |v_k|^2 \geq \dfrac{a^2}{1+b^2} \\ atan\left(\dfrac{1}{b}\right) & \text{for } |v_k|^2 < \dfrac{a^2}{1+b^2} \end{cases} \qquad \text{(Eq.23)}$$

wherein v_k is a given decision variable.

10. An echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder (142) for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for determining an echo phase offset for each decoded phase shift comprising means (500) for eliminating phase shift uncertainties related to the transmitted information from said decoded phase shift;

means (520) for averaging said echo phase offsets in order to generate an averaged offset; and

means (524) for correcting each decoded phase shift based on said averaged offset.

11. The device according to claim 10, wherein said differential phase decoder is adapted for decoding said phase shifts based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

12. The device according to claim 10 or 11, further comprising means (516) for comparing an absolute value of a symbol associated with a respective decoded phase shift with a threshold, wherein said means for averaging said phase offsets only uses phase shifts having associated therewith symbols having an absolute value exceeding said threshold.

13. The device according to one of claims 10 to 12, wherein said differential phase decoder is adapted for decoding said phase shifts based on phase differences between at least three simultaneous carriers which are equally spaced in the frequency axis direction.

14. An echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, said phase shifts defining signal points in a complex plane;

means for pre-rotating said signal points into the sector of said complex plane between -45° and +45°;

means for determining parameters (a, b) of a straight line approximating the location of said pre-rotated signal points in said complex plane;

means for determining a phase offset based on said parameters (a, b); and

means for correcting each decoded phase shift based on said phase offset.

15. The device according to claim 14, wherein said differential phase decoder comprises means for decoding phase shifts of at least three simultaneous carriers which are equally spaced in the frequency axis direction.

16. The device according to claim 14 or 15, wherein said means for determining said parameters (a, b) comprises means for performing a least squares method for selecting those parameters which minimize the deviations of said pre-rotated signal points from said straight line.

17. The device according to claim 16, wherein said means for determining said parameters (a, b) calculates said parameters (a, b) as follows:

$$b = \frac{\sum_{i=1}^{K} (x_i - \overline{x}) \cdot y_i}{\sum_{i=1}^{K} (x_i - \overline{x})^2}, \quad a = \overline{y} - \overline{x} \cdot b \qquad \text{(Eq.25)}$$

$$\overline{x} = \frac{1}{N} \sum_{i=1}^{K} x_i, \quad \overline{y} = \frac{1}{N} \sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

wherein x and y designate the coordinates of the signal points in the complex plane,

i is an index from 1 to N, and

K is the number of signal points.

18. The device according to claim 17, wherein said means for determining said phase offset (φ_k) calculates said phase offset (φ_k) as follows:

$$\varphi_k = \begin{cases} -atan\left(\dfrac{a+b\sqrt{|v_k|^2(1+b^2)-a^2}}{-ab+\sqrt{|v_k|^2(1+b^2)-a^2}}\right) & \text{for } |v_k|^2 \geq \dfrac{a^2}{1+b^2} \\ atan\left(\dfrac{1}{b}\right) & \text{for } |v_k|^2 < \dfrac{a^2}{1+b^2} \end{cases} \quad \text{(Eq.23)}$$

wherein v_k is a given decision variable.

PATENT COOPERATION TREATY

EINGEGANGEN

21. JULI 2000

From the
INTERNATIONAL PRELIMINARY EXAMINING AUTHORITY

To:

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PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Rule 71.1)

Date of mailing *(day/month/year)*		19.07.00
Applicant's or agent's file reference FH980405PCT		**IMPORTANT NOTIFICATION**
International application No. PCT/EP98/02167	International filing date *(day/month/year)* 14/04/1998	Priority date *(day/month/year)* 14/04/1998
Applicant FRAUNHOFER-GESELLSCHAFT ZUR FÖRDERUNG .... et al.		

1. The applicant is hereby notified that this International Preliminary Examining Authority transmits herewith the international preliminary examination report and its annexes, if any, established on the international application.

2. A copy of the report and its annexes, if any, is being transmitted to the International Bureau for communication to all the elected Offices.

3. Where required by any of the elected Offices, the International Bureau will prepare an English translation of the report (but not of any annexes) and will transmit such translation to those Offices.

4. **REMINDER**

   The applicant must enter the national phase before each elected Office by performing certain acts (filing translations and paying national fees) within 30 months from the priority date (or later in some Offices) (Article 39(1)) (see also the reminder sent by the International Bureau with Form PCT/IB/301).

   Where a translation of the international application must be furnished to an elected Office, that translation must contain a translation of any annexes to the international preliminary examination report. It is the applicant's responsibility to prepare and furnish such translation directly to each elected Office concerned.

   For further details on the applicable time limits and requirements of the elected Offices, see Volume II of the PCT Applicant's Guide.

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PATENT COOPERATION TREATY

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INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference	FOR FURTHER ACTION	See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)
FH980405PCT		
International application No. PCT/EP98/02167	International filing date *(day/month/year)* 14/04/1998	Priority date *(day/month/year)* 14/04/1998

International Patent Classification (IPC) or national classification and IPC
H04L27/26

Applicant

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1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 5 sheets, including this cover sheet.

   ☒ This report is also accompanied by ANNEXES, i.e. sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of 14 sheets.

3. This report contains indications relating to the following items:

I	☒	Basis of the report
II	☐	Priority
III	☐	Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
IV	☐	Lack of unity of invention
V	☒	Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations suporting such statement
VI	☐	Certain documents cited
VII	☒	Certain defects in the international application
VIII	☐	Certain observations on the international application

Date of submission of the demand	Date of completion of this report
17/08/1999	19.07.00
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized officer Snell, T Telephone No. +49 89 2399 8802

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No. PCT/EP98/02167

I. Basis of the report

1. This report has been drawn on the basis of (*substitute sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to the report since they do not contain amendments.*):

Description, pages:

1-5,16-30	as originally filed			
6-13	as received on	15/03/2000	with letter of	15/03/2000

Claims, No.:

1-18	as received on	15/03/2000	with letter of	15/03/2000

Drawings, sheets:

1/7-7/7	as originally filed

2. The amendments have resulted in the cancellation of:

- ☐ the description, pages:
- ☐ the claims, Nos.:
- ☐ the drawings, sheets:

3. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed (Rule 70.2(c)):

4. Additional observations, if necessary:

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No. PCT/EP98/02167

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	1-18
	No:	Claims	
Inventive step (IS)	Yes:	Claims	1-18
	No:	Claims	
Industrial applicability (IA)	Yes:	Claims	1-18
	No:	Claims	

2. Citations and explanations

see separate sheet

VII. Certain defects in the international application

The following defects in the form or contents of the international application have been noted:

see separate sheet

Cited document

D1: MOOSE: 'Differentially coded multi-frequency modulation for digital communications' SIGNAL PROCESSING THEORIES AND APPLICATIONS, 18 - 21 September 1990, pages 1807-1810, XP000365916 Amsterdam, NL

Re Item V

Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. The invention relates to the field of multi-carrier modulation systems (MCM, also referred to as OFDM), and in particular to a system using differential phase coding based on a phase difference between simultaneous carriers. A system of this type is disclosed in D1.

2. In a multipath environment the problem arises of echoes which result in a phase offset of the decoded signal. The aim of the present invention is to provide methods (independent claims 1 and 5) and corresponding apparatuses (independent claims 10 and 14) for performing echo phase offset correction in a multicarrier demodulation system.

3. This aim is solved in accordance with two different embodiments. According to claim 1 and corresponding apparatus claim 10, the solution involves eliminating the phase shifts due to the transmitted information from each decoded phase shift to determine an echo phase offset for each decoded phase shift, averaging the resulting offsets, and correcting each decoded phase shifts based on this average. According to the embodiment claimed in claim 5 and corresponding apparatus claim 14, the solution is based on pre-rotating signal points into one quadrant, determining parameters of a straight line approximating the location of said pre-rotated signal and determining the phase offset based on these parameters.

4. Since no prior art document is even concerned with the problem of echoes in a differentially coded MCM signal, let alone provide a solution, the subject-matter of

independent claims 1, 5, 10 and 14 is novel and involves an inventive step (Articles 33(1)-(3) PCT).

5. Claims 2-4, 6-9, 11-13 and 15-18 are dependent on one of the independent claims 1, 5, 10 or 14 and thus also meet the requirements for novelty and inventive step (Articles 33(1)-(3) PCT).

Re Item VII
Certain defects in the international application

1. The request to change the title to read "Echo Phase Offset Correction in a Multi-Carrier Demodulation System" can only be considered during the regional phase, although it is agreed that this new title more appropriately reflects the scope of the invention.

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H04L 27/26

A1

(11) International Publication Number: WO 99/53664

(43) International Publication Date: 21 October 1999 (21.10.99)

(21) International Application Number: PCT/EP98/02167

(22) International Filing Date: 14 April 1998 (14.04.98)

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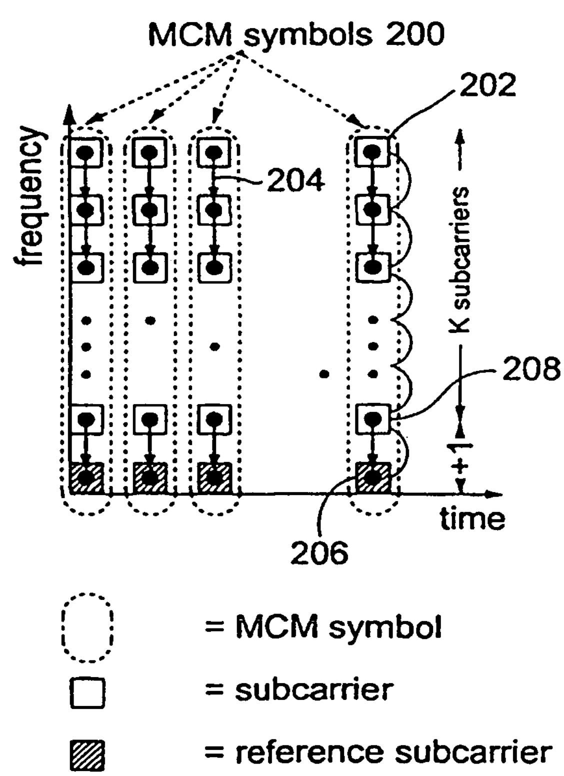
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.

(54) Title: DIFFERENTIAL CODING AND CARRIER RECOVERY FOR MULTICARRIER SYSTEMS

(57) Abstract

A method of mapping information onto at least two simultaneous carriers (202, 206, 208) having different frequencies in a multi-carrier modulation system involves the step of controlling respective parameters of the at least two carriers such that the information is differential encoded. A method of de-mapping information based on at least two simultaneous encoded carriers having different frequencies in a multi-carrier demodulation system comprises the step of recovering the information by differential decoding (142) of respective parameters of the at least two carriers. In a method of performing an echo phase offset correction in a multi-carrier demodulation system, phase shifts are differential phase decoded (142) based on a phase difference between simultaneous carriers having different frequencies. An echo phase offset is determined for each decoded phase shift by eliminating (500) phase shift uncertainties corresponding to codeable phase shifts from the decoded phase shift. The echo phase offsets are averaged (520) in order to generate an averaged offset. Finally, each decoded phase shift is corrected (524) based on the averaged offset.



09/673266

DIFFERENTIAL CODING AND CARRIER RECOVERY FOR MULTICARRIER SYSTEMS

FIELD OF THE INVENTION

The present invention relates to methods and apparatus for performing modulation and de-modulation in multi-carrier modulation systems (MCM systems) and, in particular, to methods and apparatus for differential mapping and de-mapping of information onto carriers of multi-carrier modulation symbols in such systems. Furthermore, the present invention relates to methods and apparatus for performing an echo phase offset correction when decoding information encoded onto carriers of multi-carrier modulation symbols in multi-carrier modulation systems.

BACKGROUND OF THE INVENTION

The present invention generally relates to broadcasting of digital data to mobile receivers over time-variant multipath channels. More specifically, the present invention is particularly useful in multipath environments with low channel coherence time, i.e. rapidly changing channels. In preferred embodiments, the present invention can be applied to systems implementing a multicarrier modulation scheme. Multi-carrier modulation (MCM) is also known as orthogonal frequency division multiplexing (OFDM).

In a MCM transmission system binary information is represented in the form of a complex spectrum, i.e. a distinct number of complex subcarrier symbols in the frequency domain. In the modulator a bitstream is represented by a sequence of spectra. Using an inverse Fourier-transform (IFFT) a MCM time domain signal is

produced from this sequence of spectra.

Figure 7 shows a MCM system overview. At 100 a MCM transmitter is shown. A description of such a MCM transmitter can be found, for example, in William Y. Zou, Yiyan Wu, "COFDM: AN OVERVIEW", IEEE Transactions on Broadcasting, vol. 41, No. 1, March 1995.

A data source 102 provides a serial bitstream 104 to the MCM transmitter. The incoming serial bitstream 104 is applied to a bit-carrier mapper 106 which produces a sequence of spectra 108 from the incoming serial bitstream 104. An inverse fast Fourier transform (FFT) 110 is performed on the sequence of spectra 108 in order to produce a MCM time domain signal 112. The MCM time domain signal forms the useful MCM symbol of the MCM time signal. To avoid intersymbol interference (ISI) caused by multipath distortion, a unit 114 is provided for inserting a guard interval of fixed length between adjacent MCM symbols in time. In accordance with a preferred embodiment of the present invention, the last part of the useful MCM symbol is used as the guard interval by placing same in front of the useful symbol. The resulting MCM symbol is shown at 115 in Figure 7.

A unit 116 for adding a reference symbol for each predetermined number of MCM symbols is provided in order to produce a MCM signal having a frame structure. Using this frame structure comprising useful symbols, guard intervals and reference symbols it is possible to recover the useful information from the MCM signal at the receiver side.

The resulting MCM signal having the structure shown at 118 in Figure 7 is applied to the transmitter front end 120. Roughly speaking, at the transmitter front end 120, a digital/analog conversion and an up-converting of the MCM signal is performed. Thereafter, the MCM signal is transmitted through a channel 122.

Following, the mode of operation of a MCM receiver 130 is shortly described referring to Figure 7. The MCM signal is received at the receiver front end 132. In the receiver front end 132, the MCM signal is down-converted and, furthermore, a digital/analog conversion of the down-converted signal is performed. The down-converted MCM signal is provided to a frame synchronization unit 134. The frame synchronization unit 134 determines the location of the reference symbol in the MCM symbol. Based on the determination of the frame synchronization unit 134, a reference symbol extracting unit 136 extracts the framing information, i.e. the reference symbol, from the MCM symbol coming from the receiver front end 132. After the extraction of the reference symbol, the MCM signal is applied to a guard interval removal unit 138.

The result of the signal processing performed so far in the MCM receiver are the useful MCM symbols. The useful MCM symbols output from the guard interval removal unit 138 are provided to a fast Fourier transform unit 140 in order to provide a sequence of spectra from the useful symbols. Thereafter, the sequence of spectra is provided to a carrier-bit mapper 142 in which the serial bitstream is recovered. This serial bitstream is provided to a data sink 144.

As it is clear from Figure 7, every MCM transmitter 100 must contain a device which performs mapping of the transmitted bitstreams onto the amplitudes and/or phases of the sub-carriers. In addition, at the MCM receiver 130, a device is needed for the inverse operation, i.e. retrieval of the transmitted bitstream from the amplitudes and/or phases of the sub-carriers.

For a better understanding of MCM mapping schemes, it is preferable to think of the mapping as being the assignment of one ore more bits to one or more sub-carrier symbols in the time-frequency plane. In the following, the term symbol

or signal point is used for the complex number which represents the amplitude and/or phase modulation of a subcarrier in the equivalent baseband. Whenever all complex numbers representing all subcarrier symbols are designated, the term MCM symbol is used.

DESCRIPTION OF PRIOR ART

In principle, two methods for mapping the bitstream into the time-frequency plane are used in the prior art:

A first method is a differential mapping along the time axis. When using differential mapping along the time axis one or more bits are encoded into phase and/or amplitude shifts between two subcarriers of the same center frequency in adjacent MCM symbols. Such an encoding scheme is shown in Figure 8. The arrows depicted between the sub-carrier symbols correspond to information encoded in amplitude and/or phase shifts between two subcarrier symbols.

A system applying such a mapping scheme is defined in the European Telecommunication Standard ETS 300 401 (EU147-DAB). A system compliant to this standard uses Differential Quadrature Phase Shift Keying (DQPSK) to encode every two bits into a 0, 90, 180 or 270 degrees phase difference between two subcarriers of the same center frequency which are located in MCM symbols adjacent in time.

A second method for mapping the bitstream into the time-frequency plane is a non-differential mapping. When using non-differential mapping the information carried on a subcarrier is independent of information transmitted on any other subcarrier, and the other subcarrier may differ either in frequency, i.e. the same MCM symbol, or in time, i.e. adjacent MCM symbols. A system applying such a mapping scheme is defined in the European Telecommunication Standard ETS 300 744 (DVB-T). A system compliant to this standard

uses 4,16 or 64 Quadrature Amplitude Modulation (QAM) to assign bits to the amplitude and phase of a subcarrier.

The quality with which transmitted multi-carrier modulated signals can be recovered at the receiver depends on the properties of the channel. The most interesting property when transmitting MCM signals is the time interval at which a mobile channel changes its characteristics considerably. The channel coherence time T_C is normally used to determine the time interval at which a mobile channel changes its characteristics considerably. T_C depends on the maximum Doppler shift as follows:

$$f_{Doppler,max} = v \cdot f_{carrier} \; / \; c \qquad \text{(Eq.1)}$$

with v : speed of the mobile receiver in [m/s]
$f_{carrier}$: carrier frequency of the RF signal [Hz]
c : speed of light ($3 \cdot 10^8$ m/s)

The channel coherence time T_C is often defined to be

$$T_c\big|_{50\%} = \frac{9}{16\pi f_{Doppler,max}} \quad \text{or} \quad T_c\big|_{2nd\ Def.} = \sqrt{\frac{9}{16\pi f^2_{Dopper,max}}} \qquad \text{(Eq.2)}$$

It becomes clear from the existence of more than one definition, that the channel coherence time Tc is merely a rule-of-thumb value for the stationarity of the channel. As explained above, the prior art time-axis differential mapping requires that the mobile channel be quasi stationary during several MCM symbols periods, i.e. required channel coherence time Tc >> MCM symbol period. The prior art non-differential MCM mapping only requires that the mobile channel be quasi stationary during one symbol interval, i.e. required channel coherence time ≥ MCM symbol period.

Thus, both prior art mapping schemes have specific disadvantages. For differential mapping into time axis direction the channel must be quasi stationary, i.e. the channel must not change during the transmission of two MCM

symbols adjacent in time. If this requirement is not met, the channel induced phase and amplitude changes between MCM symbols will yield an increase in bit error rate.

With non-differential mapping exact knowledge of the phase of each subcarrier is needed (i.e. coherent reception). For multipath channels, coherent reception can only be obtained if the channel impulse response is known. Therefore, a channel estimation has to be part of the receiver algorithm. The channel estimation usually needs additional sequences in the transmitted waveform which do not carry information. In case of rapidly changing channels, which necessitate update of the channel estimation at short intervals, the additional overhead can quickly lead to insufficiency of non-differential mapping.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method and an apparatus for mapping information onto sub-carrier symbols in a multi-carrier modulation system which allow correct recovering of the information after transmission through a channel even in the case the channel is not stationary during several MCM symbols.

It is a further object of the present invention to provide a method and an apparatus for performing a multi-carrier modulation of a bitstream in a digital broadcasting transmitter which allow correct recovering of the bitstream after transmission through a channel even in the case the channel is not stationary during several MCM symbols.

It is a further object of the present invention to provide a method and an apparatus for de-mapping information in order to correctly recover the information even in the case a channel through which transmission takes place is not stationary during several MCM symbols.

It is a further object of the present invention to provide a method and an apparatus for performing a demodulation of a multi-carrier modulated signal in a digital broadcasting system in order to correctly recover a bitstream encoded in the multi-carrier modulated signal even in the case a channel through which transmission takes place is not stationary during several MCM symbols.

It is a further object of the present invention to provide methods an apparatus for performing an echo phase offset correction in a multi-carrier demodulation system.

In accordance with a first aspect, the present invention provides a method of mapping information onto at least two simultaneous carriers having different frequencies in a multi-carrier modulation system, the method comprising the step of controlling respective parameters of the at least two carriers such that the information is differentially encoded.

In accordance with a second aspect, the present invention provides a method of performing a multi-carrier modulation of a bitstream in a digital broadcasting transmitter, the method comprising the steps of:

phase shift keying the bitstream by associating a respective phase shift to one or more bits of the bitstream; and

differential phase encoding the phase shifts by controlling the phase of a first carrier based on a phase of a simultaneous second carrier and the phase shift, the first and second carriers having different frequencies.

In accordance with a third aspect, the present invention provides a method of de-mapping information based on at least two simultaneous encoded carriers having different

frequencies in a multi-carrier demodulation system, the method comprising the step of recovering the information by differential decoding of respective parameters of the at least two carriers.

In accordance with a fourth aspect, the present invention provides a method of performing a demodulation of a multi-carrier modulated signal in a digital broadcasting system, the method comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

recovering bits of a bitstream from said phase shifts.

In accordance with a fifth aspect, the present invention provides a method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties corresponding to codeable phase shifts from the decoded phase shift;

averaging the echo phase offsets in order to generate an averaged offset; and

correcting each decoded phase shift based on the averaged offset.

In accordance with a sixth aspect, the present invention provides a method of performing an echo phase offset

correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

determining a phase offset based on the parameters; and

correcting each decoded phase shift based on the phase offset.

In accordance with a seventh aspect, the present invention provides a mapping device for mapping information onto at least two simultaneous carriers having different frequencies, for a multi-carrier modulation system, the device comprising means for controlling respective parameters of the at least two carriers such that the information is differential encoded.

In accordance with an eighth aspect, the present invention provides a multi-carrier modulator for performing a multi-carrier modulation of a bitstream, for a digital broad-casting transmitter, the modulator comprising:

means for phase shift keying the bitstream by associating a respective phase shift to one or more bits of the bit-stream; and

a differential phase encoder for differential phase

encoding the phase shifts by controlling the phase of a first carrier based on a phase of a simultaneous second carrier and the phase shift, the first and second carriers having different frequencies.

In accordance with a ninth aspect, the present invention provides a de-mapping device for de-mapping information based on at least two simultaneous encoded carriers having different frequencies, for a multi-carrier demodulation system, the de-mapping device comprising means for recovering the information by differential decoding of respective parameters of the at least two carriers.

In accordance with a tenth aspect, the present invention provides a demodulator for demodulating a multi-carrier modulated signal, for a digital broadcasting system, the demodulator comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for recovering bits of a bitstream from the phase shifts.

In accordance with an eleventh aspect, the present invention provides an echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties corresponding to codeable phase shifts from the decoded phase shift;

means for averaging the echo phase offsets in order to generate an averaged offset; and

means for correcting each decoded phase shift based on the averaged offset.

In accordance with a twelfth aspect, the present invention provides an echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

means for pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

means for determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

means for determining a phase offset based on the parameters; and

means for correcting each decoded phase shift based on the phase offset.

The present invention provides a mapping process, suitable for multicarrier (OFDM) digital broadcasting over rapidly changing multipath channels, comprising differential encoding of the data along the frequency axis such that there is no need for channel stationarity exceeding one multicarrier symbol.

When using the inventive mapping process along the frequency axis it is preferred to make use of a receiver algorithm that will correct symbol phase offsets that can be caused by

channel echoes.

The present invention provides a mapping scheme for multi-carrier modulation which renders the transmission to a certain extent independent of rapid changes in the multipath channel without introducing a large overhead to support channel estimation. Especially systems with high carrier frequencies and/or high speeds of the mobile carrying the receiving unit can benefit from the invention.

Thus, the present invention provides a mapping scheme that does not exhibit the two problems of the prior art systems described above. The mapping scheme in accordance with the present invention is robust with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

According to a preferred embodiment of the present invention, the controlled respective parameters of the subcarriers are the phases thereof, such that the information is differentially phase encoded. However, the controlled respective parameters of the subcarriers can be the amplitudes thereof as well, such that the information is differential amplitude encoded.

In accordance with the present invention, mapping is also differential, however, not into time axis direction but into frequency axis direction. Thus, the information is not contained in the phase shift between subcarriers adjacent in time but in the phase shift between subcarriers adjacent in frequency. Differential mapping along the frequency axis has two advantages when compared to prior art mapping schemes. Because of differential mapping, no estimation of the absolute phase of the subcarriers is required. Therefore, channel estimation and the related overhead are not necessary. By choosing the frequency axis as direction for differentially encoding the information bitstream, the requirement that the channel must be stationary during

several MCM symbols can be dropped. The channel only has to remain unchanged during the current MCM symbol period. Therefore, like for non-differential mapping it holds that

required channel coherence time $\geq$ MCM symbol period.

The present invention further provides methods and apparatus for correction of phase distortions that can be caused by channel echoes. As described above, differential mapping into frequency axis direction solves problems related to the stationarity of the channel. However, differential mapping into frequency axis direction may create a new problem. In multipath environments, path echoes succeeding or preceding the main path can lead to systematic phase offsets between subcarriers in the same MCM symbol. In this context, the main path is thought of being the path echo with the highest energy content. The main path echo will determine the position of the FFT window in the receiver of an MCM system.

In preferred embodiments of the present invention, the information will be contained in a phase shift between adjacent subcarriers of the same MCM symbol. If not corrected for, the path echo induced phase offset between two subcarriers can lead to an increase in bit error rate. Therefore, application of the MCM mapping scheme presented in this invention will preferably be used in combination with a correction of the systematic subcarrier phase offsets in case of a multipath channel.

The introduced phase offset can be explained from the shifting property of the Discrete Fourier Transform (DFT):

$$x\left[((n-m))_N\right] \xleftrightarrow{DFT} X[k]e^{-j\frac{2\pi}{N}km} \qquad \text{(Eq.3)}$$

with $x[n]$: sampled time domain signal ($0 \leq n \leq N-1$)

$X[k]$: DFT transformed frequency domain signal ($0 \leq k \leq N-1$)

N : length of DFT

$(...)_N$: cyclic shift of the DFT window in the time
m : length of DFT-Shift in the time domain

Equation 3 shows, that in a multipath channel, echoes following the main path will yield a subcarrier dependent phase offset. After differential demapping in the frequency axis direction at the receiver, a phase offset between two neighboring symbols remains. Because the channel induced phase offsets between differentially demodulated symbols are systematic errors, they can be corrected by an algorithm.

In the context of the following specification, algorithms which help correcting the phase shift are called Echo Phase Offset Correction (EPOC) algorithms. Two such algorithms are described as preferred embodiments for the correction of phase distortions that can be caused by channel echoes. These algorithms yield a sufficient detection security for MCM frequency axis mapping even in channels with echoes close to the limits of the guard interval.

In principle, an EPOC algorithm must calculate the echo induced phase offset from the signal space constellation following the differential demodulation and subsequently correct this phase offset.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following, preferred embodiments of the present invention will be explained in detail on the basis of the drawings enclosed, in which:

Figure 1 shows a schematic view representing the inventive mapping scheme;

Figure 2 shows a functional block diagram of an embodiment of a mapping device in accordance with the present invention;

Figures 3A and 3B show scatter diagrams of the output of an differential de-mapper of a MCM receiver for illustrating the effect of an echo phase offset correction;

Figure 4 shows a schematic block diagram for illustrating the position and the functionality of an echo phase offset correction unit;

Figure 5 shows a schematic block diagram of an embodiment of an echo phase offset correction device according to the present invention;

Figure 6 shows schematic views for illustrating a projection performed by another embodiment of an echo phase offset correction device according to the present invention;

Figure 7 shows a schematic block diagram of a generic multi-carrier modulation system; and

Figure 8 shows a schematic view representing a prior art differential mapping scheme.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Although the present invention is explained mainly referring to a MCM system using differential phase encoding as generally shown in Figure 7, it is clear that the present invention can be used in connection with different transmission systems using differential amplitude encoding or a combined differential amplitude/phase encoding, for example.

In a preferred embodiment thereof, the present invention is applied to a MCM system as shown in Figure 7. With respect

to this MCM system, the present invention relates to the bit-carrier mapper 106 of the MCM transmitter 100 and the carrier-bit mapper 142 of the MCM receiver 130, which are depicted with a shaded background in Figure 7.

An preferred embodiment of an inventive mapping scheme used by the bit-carrier mapper 106 is depicted in Figure 1. A number of MCM symbols 200 is shown in Figure 1. Each MCM symbol 200 comprises a number of sub-carrier symbols 202. The arrows 204 in Fig. 1 illustrate information encoded between two sub-carrier symbols 202. As can be seen from the arrows 204, the bit-carrier mapper 106 uses a differential mapping within one MCM symbol along the frequency axis direction.

In the embodiment shown in Figure 1, the first sub-carrier (k=0) in an MCM symbol 200 is used as a reference sub-carrier 206 (shaded) such that information is encoded between the reference sub-carrier and the first active carrier 208. The other information of a MCM symbol 200 is encoded between active carriers, respectively.

Thus, for every MCM symbol an absolute phase reference exists. In accordance with Figure 1, this absolute phase reference is supplied by a reference symbol inserted into every MCM symbol (k=0). The reference symbol can either have a constant phase for all MCM symbols or a phase that varies from MCM symbol to MCM symbol. A varying phase can be obtained by replicating the phase from the last subcarrier of the MCM symbol preceding in time.

In Figure 2 a preferred embodiment of a device for performing a differential mapping along the frequency axis is shown. Referring to Figure 2, assembly of MCM symbols in the frequency domain using differential mapping along the frequency axis according to the present invention is described.

Figure 2 shows the assembly of one MCM symbol with the following parameters:

N_{FFT} designates the number of complex coefficients of the discrete Fourier transform, number of subcarriers respectively.

K designates the number of active carriers. The reference carrier is not included in the count for K.

According to Figure 2, a quadrature phase shift keying (QPSK) is used for mapping the bitstream onto the complex symbols. However, other M-ary mapping schemes (MPSK) like 2-PSK, 8-PSK, 16-QAM, 16-APSK, 64-APSK etc. are possible.

Furthermore, for ease of filtering and minimization of aliasing effects some subcarriers are not used for encoding information in the device shown in Figure 2. These sub-carriers, which are set to zero, constitute the so-called guard bands on the upper and lower edges of the MCM signal spectrum.

At the input of the mapping device shown in Figure 2, complex signal pairs b0[k], b1[k] of an input bitstream are received. K complex signal pairs are assembled in order to form one MCM symbol. The signal pairs are encoded into the K differential phase shifts phi[k] needed for assembly of one MCM symbol. In this embodiment, mapping from Bits to the 0, 90, 180 and 270 degrees phase shifts is performed using Gray Mapping in a quadrature phase shift keying device 220.

Gray mapping is used to prevent that differential detection phase errors smaller than 135 degrees cause double bit errors at the receiver.

Differential phase encoding of the K phases is performed in a differential phase encoder 222. At this stage of processing, the K phases phi[k] generated by the QPSK Gray

mapper are differentially encoded. In principal, a feedback loop 224 calculates a cumulative sum over all K phases. As starting point for the first computation (k = 0) the phase of the reference carrier 226 is used. A switch 228 is provided in order to provide either the absolute phase of the reference subcarrier 226 or the phase information encoded onto the preceding (i.e. z^{-1}, where z^{-1} denotes the unit delay operator) subcarrier to a summing point 230. At the output of the differential phase encoder 222, the phase information theta[k] with which the respective subcarriers are to be encoded is provided. In preferred embodiments of the present invention, the subcarriers of a MCM symbol are equally spaced in the frequency axis direction.

The output of the differential phase encoder 222 is connected to a unit 232 for generating complex subcarrier symbols using the phase information theta[k]. To this end, the K differentially encoded phases are converted to complex symbols by multiplication with

$$\text{factor} * e^{j*[2*pi*(theta[k] + PHI)]} \quad \text{(Eq.4)}$$

wherein factor designates a scale factor and PHI designates an additional angle. The scale factor and the additional angle PHI are optional. By choosing PHI = 45° a rotated DQPSK signal constellation can be obtained.

Finally, assembly of a MCM symbol is effected in an assembling unit 234. One MCM symbol comprising N_{FFT} sub-carriers is assembled from N_{FFT}-K-1 guard band symbols which are "zero", one reference subcarrier symbol and K DQPSK subcarrier symbols. Thus, the assembled MCM symbol 200 is composed of K complex values containing the encoded information, two guard bands at both sides of the N_{FFT} complex values and a reference subcarrier symbol.

The MCM symbol has been assembled in the frequency domain. For transformation into the time domain an inverse discrete

Fourier transform (IDFT) of the output of the assembling unit 234 is performed by a transformator 236. In preferred embodiments of the present invention, the transformator 236 is adapted to perform a fast Fourier transform (FFT).

Further processing of the MCM signal in the transmitter as well as in the receiver is as described above referring to Figure 7.

At the receiver a de-mapping device 142 (Figure 7) is needed to reverse the operations of the mapping device described above referring to Figure 2. The implementation of the demapping device is straightforward and, therefore, need not be described herein in detail.

However, systematic phase shifts stemming from echoes in multipath environments may occur between subcarriers in the same MCM symbol. This phase offsets can cause bit errors when demodulating the MCM symbol at the receiver.

Thus, it is preferred to make use of an algorithm to correct the systematic phase shifts stemming from echoes in multi-path environments. Preferred embodiments of echo phase offset correction algorithms are explained hereinafter referring to Figures 3 to 6.

In Figures 3A and 3B, scatter diagrams at the output of a differential demapper of a MCM receiver are shown. As can be seen from Figure 3A, systematic phase shifts between subcarriers in the same MCM symbol cause a rotation of the demodulated phase shifts with respect to the axis of the complex coordinate system. In Figure 3B, the demodulated phase shifts after having performed an echo phase offset correction are depicted. Now, the positions of the signal points are substantially on the axis of the complex coordinate system. These positions correspond to the modulated phase shifts of 0°, 90°, 180° and 270°, respectively.

An echo phase offset correction algorithm (EPOC algorithm) must calculate the echo induced phase offset from the signal space constellation following the differential demodulation and subsequently correct this phase offset.

For illustration purposes, one may think of the simplest algorithm possible which eliminates the symbol phase before computing the mean of all phases of the subcarriers. To illustrate the effect of such an EPOC algorithm, reference is made to the two scatter diagrams of subcarriers symbols contained in one MCM symbol in Figures 3A and 3B. This scatter diagrams have been obtained as result of an MCM simulation. For the simulation a channel has been used which might typically show up in single frequency networks. The echoes of this channel stretched to the limits of the MCM guard interval. The guard interval was chosen to be 25% of the MCM symbol duration in this case.

Figure 4 represents a block diagram for illustrating the position and the functionality of an echo phase offset correction device in a MCM receiver. The signal of a MCM transmitter is transmitted through the channel 122 (Figures 4 and 7) and received at the receiver frontend 132 of the MCM receiver. The signal processing between the receiver frontend and the fast Fourier transformator 140 has been omitted in Figure 4. The output of the fast Fourier transformator is applied to the de-mapper, which performs a differential de-mapping along the frequency axis. The output of the de-mapper are the respective phase shifts for the subcarriers. The phase offsets of this phase shifts which are caused by echoes in multipath environments are visualized by a block 400 in Figure 4 which shows an example of a scatter diagram of the subcarrier symbols without an echo phase offset correction.

The output of the de-mapper 142 is applied to the input of an echo phase offset correction device 402. The echo phase

offset correction device 402 uses an EPOC algorithm in order to eliminate echo phase offsets in the output of the de-mapper 142. The result is shown in block 404 of Figure 4, i.e. only the encoded phase shifts, 0°, 90°, 180° or 270° are present at the output of the correction device 402. The output of the correction device 402 forms the signal for the metric calculation which is performed in order to recover the bitstream representing the transmitted information.

A first embodiment of an EPOC algorithm and a device for performing same is now described referring to Figure 5.

The first embodiment of an EPOC algorithm starts from the assumption that every received differentially decoded complex symbol is rotated by an angle due to echoes in the multipath channel. For the subcarriers equal spacing in frequency is assumed since this represents a preferred embodiment of the present invention. If the subcarriers were not equally spaced in frequency, a correction factor would have to be introduced into the EPOC algorithm.

Figure 5 shows the correction device 402 (Figure 4) for performing the first embodiment of an EPOC algorithm.

From the output of the de-mapper 142 which contains an echo phase offset as shown for example in Figure 3A, the phase shifts related to transmitted information must first be discarded. To this end, the output of the de-mapper 142 is applied to a discarding unit 500. In case of a DQPSK mapping, the discarding unit can perform a "$(.)^4$" operation. The unit 500 projects all received symbols into the first quadrant. Therefore, the phase shifts related to transmitted information is eliminated from the phase shifts representing the subcarrier symbols. The same effect could be reached with a modulo-4 operation.

Having eliminated the information related symbol phases in unit 500, the first approach to obtain an estimation would

be to simply compute the mean value over all symbol phases of one MCM symbol. However, it is preferred to perform a threshold decision before determining the mean value over all symbol phases of one MCM symbol. Due to Rayleigh fading some of the received symbols may contribute unreliable information to the determination of the echo phase offset. Therefore, depending on the absolute value of a symbol, a threshold decision is performed in order to determine whether the symbol should contribute to the estimate of the phase offset or not.

Thus, in the embodiment shown in Fig. 5, a threshold decision unit 510 is included. Following the unit 500 the absolute value and the argument of a differentially decoded symbol is computed in respective computing units 512 and 514. Depending on the absolute value of a respective symbol, a control signal is derived. This control signal is compared with a threshold value in a decision circuit 516. If the absolute value, i.e. the control signal thereof, is smaller than a certain threshold, the decision circuit 516 replaces the angle value going into the averaging operation by a value equal to zero. To this end, a switch is provided in order to disconnect the output of the argument computing unit 514 from the input of the further processing stage and connects the input of the further processing stage with a unit 518 providing a constant output of "zero".

An averaging unit 520 is provided in order to calculate a mean value based on the phase offsets φ_i determined for the individual subcarrier symbols of a MCM symbol as follows:

$$\bar{\varphi} = 1/K \sum_{i=1}^{K} \varphi_i \qquad \text{(Eq.5)}$$

In the averaging unit 520, summation over K summands which have not been set to zero in the unit 516 is performed. The output of the averaging unit 520 is provided to a hold unit

522 which holds the output of the averaging unit 520 K times. The output of the hold unit 522 is connected with a phase rotation unit 524 which performs the correction of the phase offsets of the K complex signal points on the basis of the mean value $\overline{\varphi}$.

The phase rotation unit 524 performs the correction of the phase offsets by making use of the following equation:

$$v_k' = v_k \cdot e^{-j\overline{\varphi}} \qquad \text{(Eq.6)}$$

In this equation, v_k' designates the K phase corrected differentially decoded symbols for input into the soft-metric calculation, whereas v_k designates the input symbols. As long as a channel which is quasi stationary during the duration of one MCM symbols can be assumed, using the mean value over all subcarriers of one MCM symbol will provide correct results.

A buffer unit 527 may be provided in order to buffer the complex signal points until the mean value of the phase offsets for one MCM symbol is determined. The output of the phase rotation unit 524 is applied to the further processing stage 526 for performing the soft-metric calculation.

With respect to the results of the above echo phase offset correction, reference is made again to Figures 3A and 3B. The two plots stem from a simulation which included the first embodiment of an echo phase offset correction algorithm described above. At the instant of the scatter diagram snapshot shown in Figure 3A, the channel obviously distorted the constellation in a way, that a simple angle rotation is a valid assumption. As shown in Figure 3B, the signal constellation can be rotated back to the axis by applying the determined mean value for the rotation of the differentially detected symbols.

A second embodiment of an echo phase offset correction

algorithm is described hereinafter. This second embodiment can be preferably used in connection with multipath channels that have up to two strong path echoes. The algorithm of the second embodiment is more complex than the algorithm of the first embodiment.

What follows is a mathematical derivation of the second embodiment of a method for echo phase offset correction. The following assumptions can be made in order to ease the explanation of the second embodiment of an EPOC algorithm.

In this embodiment, the guard interval of the MCM signal is assumed to be at least as long as the impulse response h[q], q = 0, 1, ..., Qh-1 of the multipath channel.

At the transmitter every MCM symbol is assembled using frequency axis mapping explained above. The symbol of the reference subcarrier equals 1, i.e. 0 degree phase shift. The optional phase shift PHI equals zero, i.e. the DQPSK signal constellation is not rotated.

Using an equation this can be expressed as

$$a_k = a_{k-1} a_k^{inc} \qquad \text{(Eq.7)}$$

with

k : index k = 1,2,...,K of the active subcarrier;

$a_k^{inc} = e^{j\frac{\pi}{2}m}$: complex phase increment symbol; m=0,1,2,3 is the QPSK symbol number which is derived from Gray encoding pairs of 2 Bits;

$a_0 = 1$: symbol of the reference subcarrier.

At the DFT output of the receiver the decision variables

$$e_k = a_k H_k \qquad \text{(Eq.8)}$$

are obtained with

$$H_k = \sum_{i=0}^{Q_h-1} h[i]\cdot e^{-j\frac{2\pi}{K}ki} \qquad \text{(Eq.9)}$$

being the DFT of the channel impulse response $h[q]$ at position k.

With $|a_k|^2 = 1$ the differential demodulation yields

$$v_k = e_k \cdot e_{k-1}^{*} = a_k^{inc} H_k H_{k-1}^{*} \qquad \text{(Eq.10)}$$

For the receiver an additional phase term φ_k is introduced, which shall be used to correct the systematic phase offset caused by the channel. Therefore, the final decision variable at the receiver is

$$v'_k = v_k \cdot e^{j\varphi_k} = a_k^{inc} \cdot e^{j\varphi_k} \cdot H_k \cdot H_{k-1}^{*} \qquad \text{(Eq.11)}$$

As can be seen from the Equation 11, the useful information a_k^{inc} is weighted with the product $e^{j\varphi_k} \cdot H_k \cdot H^*_{k-1}$ (rotation and effective transfer function of the channel). This product must be real-valued for an error free detection. Considering this, it is best to choose the rotation angle to equal the negative argument of $H_k \cdot H^*_{k-1}$. To derive the desired algorithm for 2-path channels, the nature of $H_k \cdot H^*_{k-1}$ is investigated in the next section.

It is assumed that the 2-path channel exhibits two echoes with energy content unequal zero, i.e. at least two dominant echoes. This assumption yields the impulse response

$$h[q] = c_1\delta_0[q] + c_2\delta_0[q - q_0] \qquad \text{(Eq.12)}$$

with

c_1, c_2 : complex coefficients representing the path echoes;

q_0 : delay of the second path echo with respect to the first path echo;

δ_0 : Dirac pulse; $\delta_0[k] = 1$ for $k = 0$
$\delta_0[k] = 0$ else

The channel transfer function is obtained by applying a DFT (Eq.9) to Equation 12:

$$H_k = H\left(e^{j\frac{2\pi}{K}k}\right) = c_1 + c_2 \cdot e^{-j\frac{2\pi}{K}kq_0} \qquad \text{(Eq.13)}$$

With Equation 13 the effective transfer function for differential demodulation along the frequency axis is:

$$\begin{aligned} H_k \cdot H_{k-1}^* &= \left(c_1 + c_2 e^{-j\frac{2\pi}{K}kq_0}\right) \cdot \left(c_1^* + c_2^* e^{+j\frac{2\pi}{K}(k-1)q_0}\right) \\ &= c_a + c_b \cos\left(\frac{\pi}{K} q_0 (2k-1)\right) \end{aligned} \qquad \text{(Eq.14)}$$

Assuming a noise free 2-path channel, it can be observed from Equation 14 that the symbols on the receiver side are located on a straight line in case the symbol 1+j0 has been send (see above assumption). This straight line can be characterized by a point

$$c_a = |c_1|^2 + |c_2|^2 \cdot e^{-j\frac{2\pi}{K}q_0} \qquad \text{(Eq.15)}$$

and the vector

$$c_b = 2c_1c_2^* \cdot e^{-j\frac{\pi}{K}q_0} \qquad \text{(Eq.16)}$$

which determines its direction.

With the above assumptions, the following geometric derivation can be performed. A more suitable notation for the geometric derivation of the second embodiment of an EPOC algorithm is obtained if the real part of the complex plane is designated as $x = \mathrm{Re}\{z\}$, the imaginary part as $y = \mathrm{Im}\{z\}$, respectively, i.e. $z = x+jy$. With this new notation, the

straight line, on which the received symbols will lie in case of a noise-free two-path channel, is

$$f(x) = a + b \cdot x \qquad \text{(Eq.17)}$$

with

$$a = \mathrm{Im}\{c_a\} - \frac{\mathrm{Re}\{c_a\}}{\mathrm{Re}\{c_b\}} \cdot \mathrm{Im}\{c_b\} \qquad \text{(Eq.18)}$$

and

$$b = -\frac{\mathrm{Im}\{c_a\} - \frac{\mathrm{Re}\{c_a\}}{\mathrm{Re}\{c_b\}} \cdot \mathrm{Im}\{c_b\}}{\mathrm{Re}\{c_a\} - \frac{\mathrm{Im}\{c_a\}}{\mathrm{Im}\{c_b\}} \cdot \mathrm{Re}\{c_b\}} \qquad \text{(Eq.19)}$$

Additional noise will spread the symbols around the straight line given by Equations 17 to 19. In this case Equation 19 is the regression curve for the cluster of symbols.

For the geometric derivation of the second embodiment of an EPOC algorithm, the angle φ_K from Equation 11 is chosen to be a function of the square distance of the considered symbol from the origin:

$$\varphi_K = f_K(|z|^2) \qquad \text{(Eq.20)}$$

Equation 20 shows that the complete signal space is distorted (torsion), however, with the distances from the origin being preserved.

For the derivation of the algorithm of the second embodiment, $f_K(\cdot)$ has to be determined such that all decision variables v'_K (assuming no noise) will come to lie on the real axis:

$$\mathrm{Im}\left\{\left(x + jf(x)\right)\cdot e^{j f_K(|z|^2)}\right\} = 0 . \tag{Eq.21}$$

Further transformations of Equation 21 lead to a quadratic equation which has to be solved to obtain the solution for φ_k.

In case of a two-path channel, the echo phase offset correction for a given decision variable v_k is

$$v_k' = v_k \cdot e^{j\varphi_k} \tag{Eq.22}$$

with

$$\varphi_k = \begin{cases} -atan\left(\dfrac{a + b\sqrt{|v_k|^2\left(1+b^2\right) - a^2}}{-ab + \sqrt{|v_k|^2\left(1+b^2\right) - a^2}}\right) & \text{for} \quad |v_k|^2 \geq \dfrac{a^2}{1+b^2} \\ atan\left(\dfrac{1}{b}\right) & \text{for} \quad |v_k|^2 < \dfrac{a^2}{1+b^2} \end{cases} \tag{Eq.23}$$

From the two possible solutions of the quadratic equation mentioned above, Equation 23 is the one solution that cannot cause an additional phase shift of 180 degrees.

The two plots in Figure 6 show the projection of the EPOC algorithm of the second embodiment for one quadrant of the complex plane. Depicted here is the quadratic grid in the sector $|\arg(z)| \leq \pi/4$ and the straight line $y = f(x) = a+b\cdot x$ with $a = -1.0$ and $b = 0.5$ (dotted line). In case of a noise-free channel, all received symbols will lie on this straight line if 1+j0 was send. The circle shown in the plots determines the boarder line for the two cases of Equation 23. In the left part, Figure 6 shows the situation before the projection, in the right part, Figure 6 shows the situation after applying the projection algorithm. By looking on the left part, one can see, that the straight line now lies on the real axis with 2+j0 being the fix point of the projection. Therefore, it can be concluded that the

echo phase offset correction algorithm according to the second embodiment fulfills the design goal.

Before the second embodiment of an EPOC algorithm can be applied, the approximation line through the received symbols has to be determined, i.e. the parameters a and b must be estimated. For this purpose, it is assumed that the received symbols lie in sector $|\arg(z)| \leq \pi/4$, if 1+j0 was sent. If symbols other than 1+j0 have been sent, a modulo operation can be applied to project all symbols into the desired sector. Proceeding like this prevents the necessity of deciding on the symbols in an early stage and enables averaging over all signal points of one MCM symbol (instead of averaging over only ¼ of all signal points).

For the following computation rule for the EPOC algorithm of the second embodiment, x_i is used to denote the real part of the i-th signal point and y_i for its imaginary part, respectively (i = 1, 2,..., K). Altogether, K values are available for the determination. By choosing the method of least squares, the straight line which has to be determined can be obtained by minimizing

$$(a,b) = \underset{(\tilde{a},\tilde{b})}{\mathit{argmin}} \sum_{i=1}^{K} \left(y_i - \left(\tilde{a} + \tilde{b} \cdot x_i\right)\right)^2 \qquad \text{(Eq.24)}$$

The solution for Equation 24 can be found in the laid open literature. It is

$$b = \frac{\sum_{i=1}^{K} \left(x_i - \bar{x}\right) \cdot y_i}{\sum_{i=1}^{K} \left(x_i - \bar{x}\right)^2}, \quad a = \bar{y} - \bar{x} \cdot b \qquad \text{(Eq.25)}$$

with mean values

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{K} x_i, \quad \bar{y} = \frac{1}{N} \sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

If necessary, an estimation method with higher robustness

can be applied. However, the trade-off will be a much higher computational complexity.

To avoid problems with the range in which the projection is applicable, the determination of the straight line should be separated into two parts. First, the cluster's centers of gravity are moved onto the axes, following, the signal space is distorted. Assuming that a and b are the original parameters of the straight line and α is the rotation angle, $f_{K(.)}$ has to be applied with the transformed parameters

$$b' = \frac{b \cdot \cos(\alpha) - \sin(\alpha)}{\cos(\alpha) + b \cdot \sin(\alpha)}, \qquad a' = a \cdot \left(\cos(\alpha) - b' \cdot \sin(\alpha)\right) \qquad \text{(Eq.27)}$$

Besides the two EPOC algorithms explained above section, different algorithms can be designed that will, however, most likely exhibit a higher degree of computational complexity.

The new mapping method for Multicarrier Modulation schemes presented herein consists in principal of two important aspects. Differential mapping within one MCM symbol along the frequency axis direction and correction of the channel echo related phase offset on the subcarriers at the receiver side. The advantage of this new mapping scheme is its robustness with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

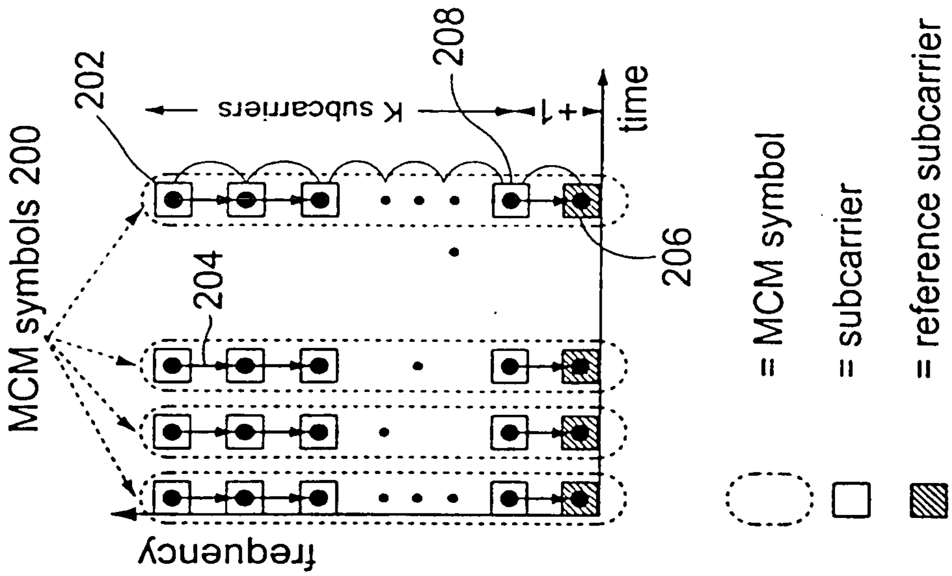

MCM symbols 200
202
204
206
208
K subcarriers
1
frequency
time
= MCM symbol
= subcarrier
= reference subcarrier

FIG.1

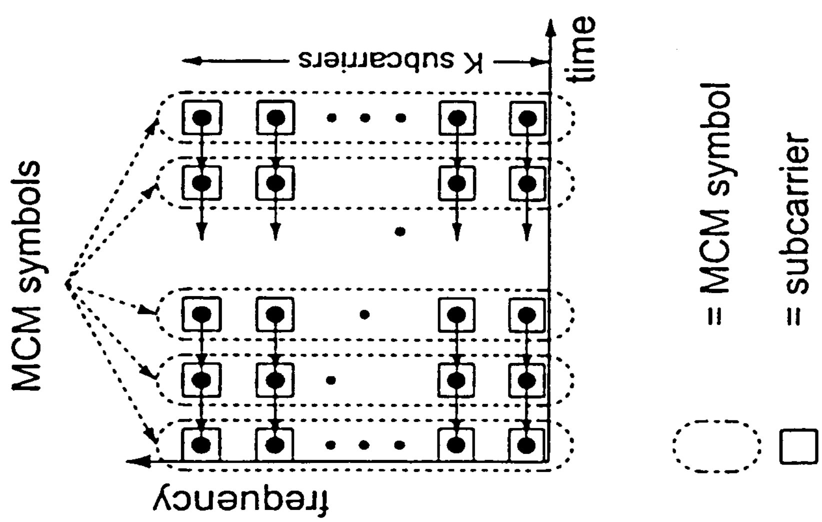

MCM symbols
K subcarriers
frequency
time
= MCM symbol
= subcarrier

FIG.8

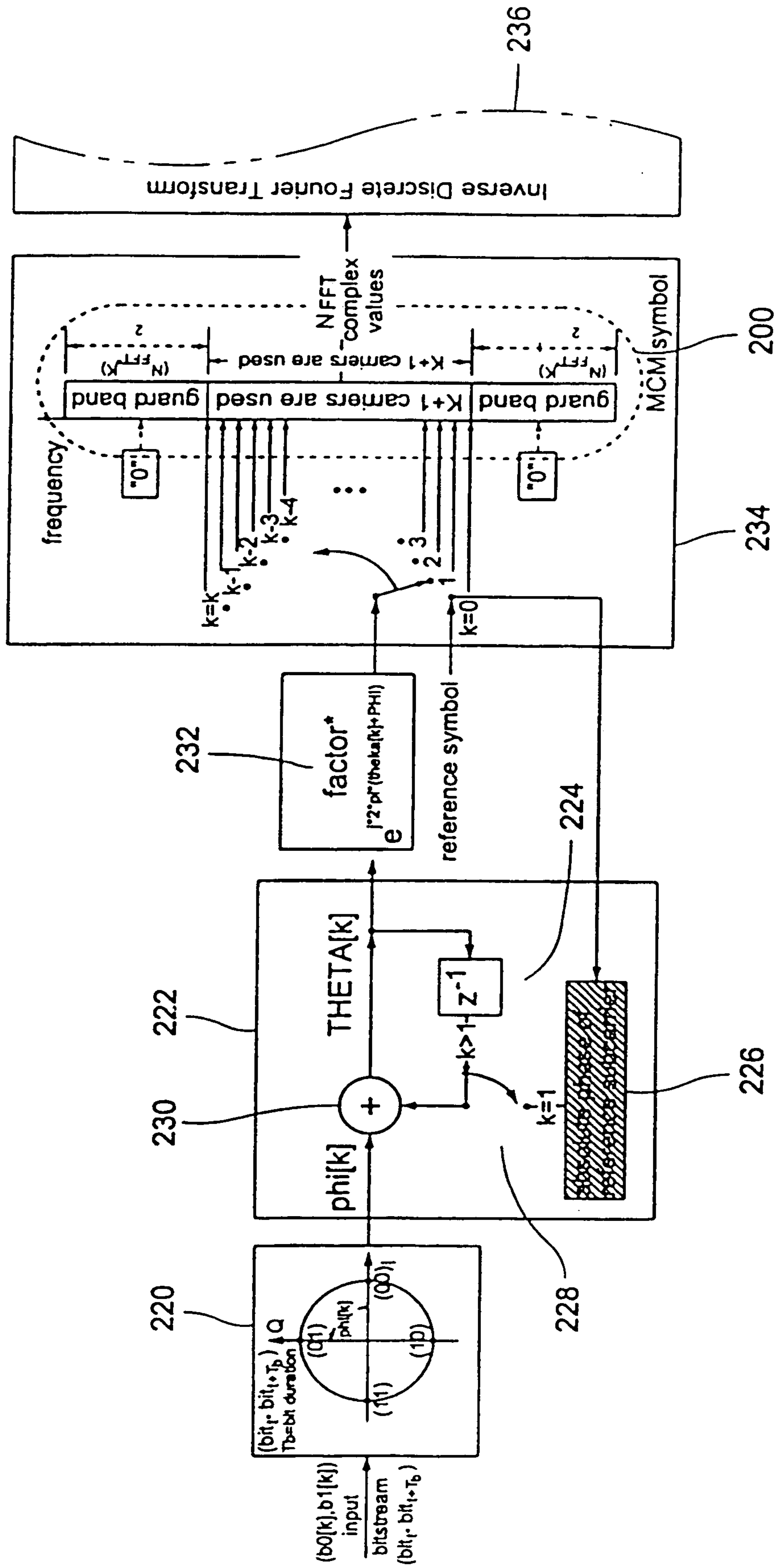
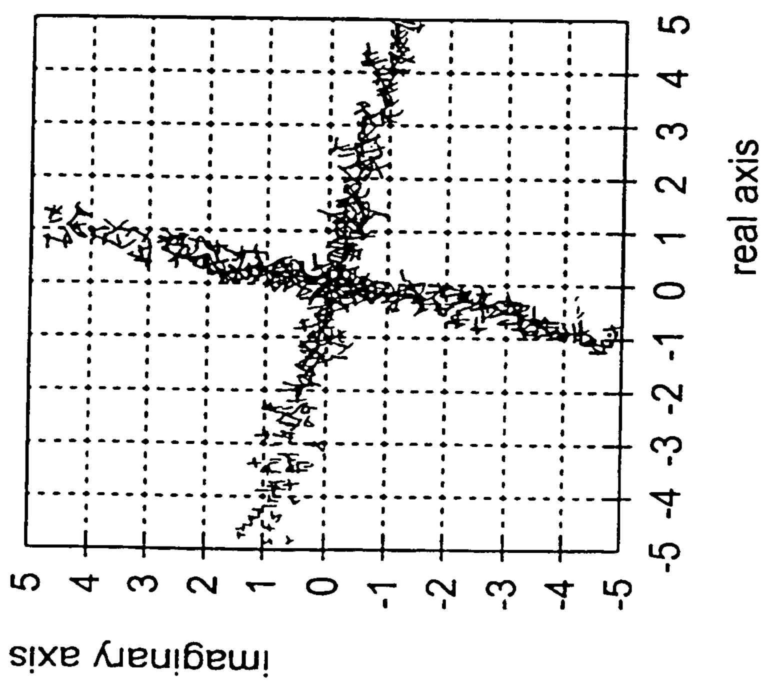

236
Inverse Discrete Fourier Transform
NFFT complex values
frequency
"0"
guard band
K+1 carriers are used
MCM symbol
200
234
k=0
reference symbol
factor*
232
THETA[k]
224
z^-1
222
phi[k]
230
k>1
k=1
226
220
Q
228
input bitstream
(b0[k],b1[k])
Tb=bit duration

FIG.2


imaginary axis
real axis
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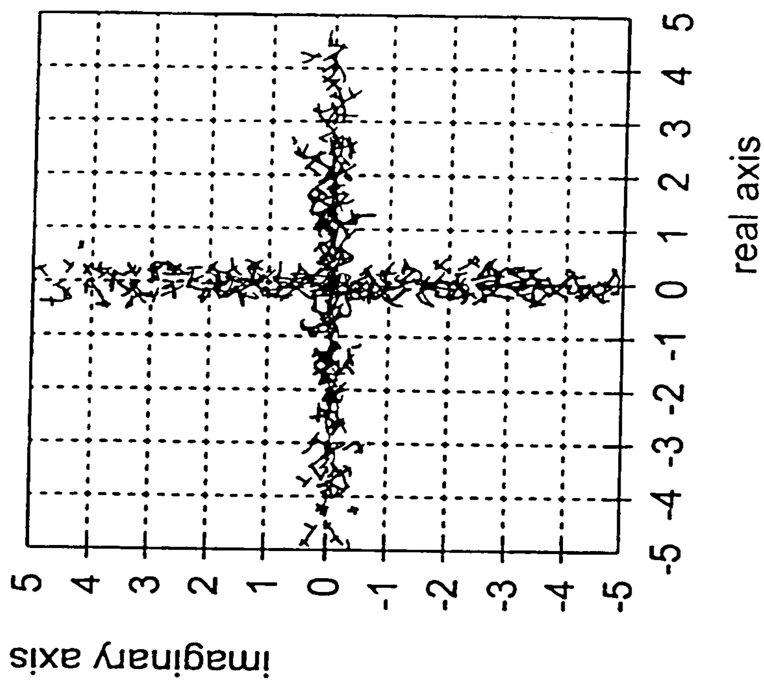
-5 -4 -3 -2 -1 0 1 2 3 4 5

FIG.3A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real axis
5 4 3 2 1 0 -1 -2 -3 -4 -5
-5 -4 -3 -2 -1 0 1 2 3 4 5

FIG.3B

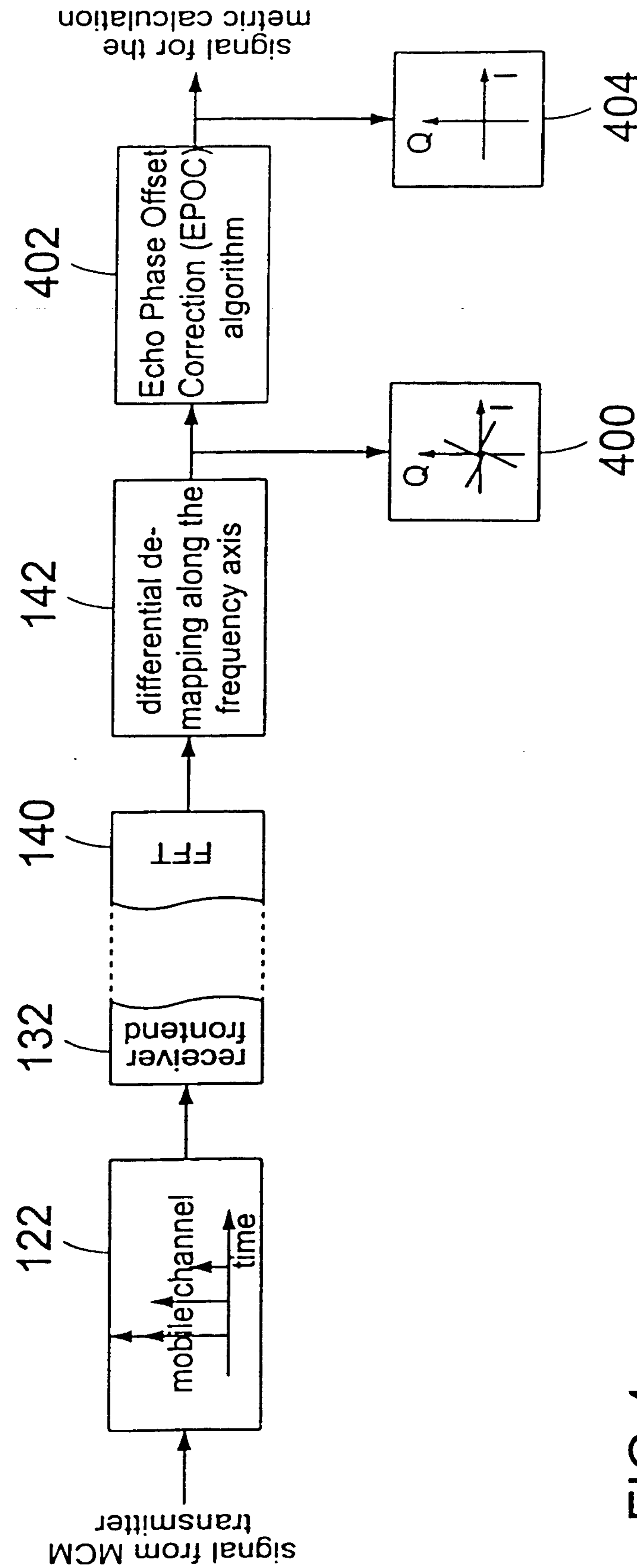
signal from MCM transmitter
122
mobile channel
time
132
receiver frontend
140
FFT
142
differential de-mapping along the frequency axis
400
Q
I
402
Echo Phase Offset Correction (EPOC) algorithm
404
Q
I
signal for the metric calculation

FIG.4

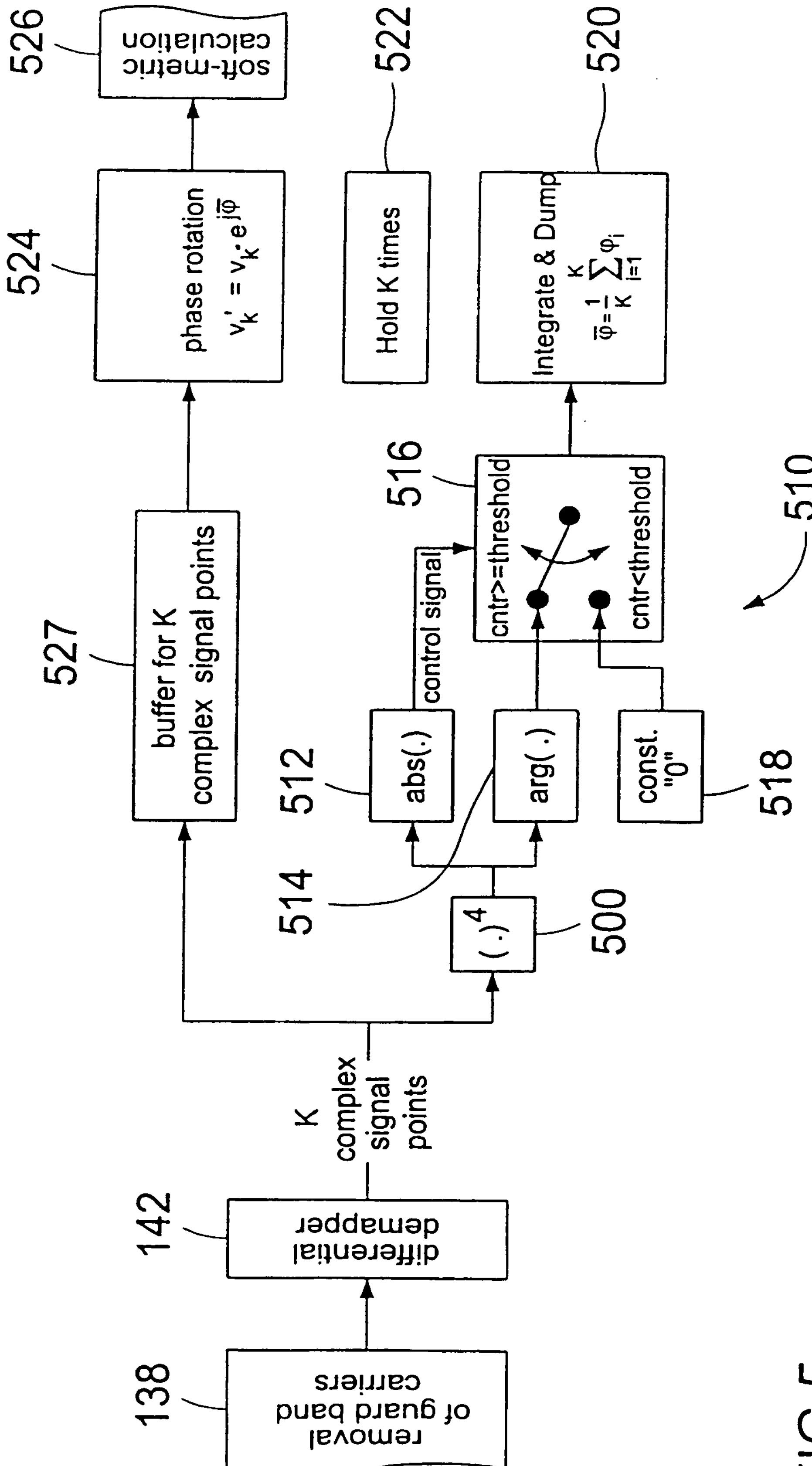
138
removal of guard band carriers
142
differential demapper
K complex signal points
500
$(\cdot)^4$
512
abs(.)
514
arg(.)
518
const. "0"
control signal
516
cntr>=threshold
cntr<threshold
510
527
buffer for K complex signal points
524
phase rotation
$v_k' = v_k \cdot e^{j\bar{\varphi}}$
526
soft-metric calculation
522
Hold K times
520
Integrate & Dump
$\bar{\varphi} = \frac{1}{K}\sum_{i=1}^{K}\varphi_i$

FIG.5

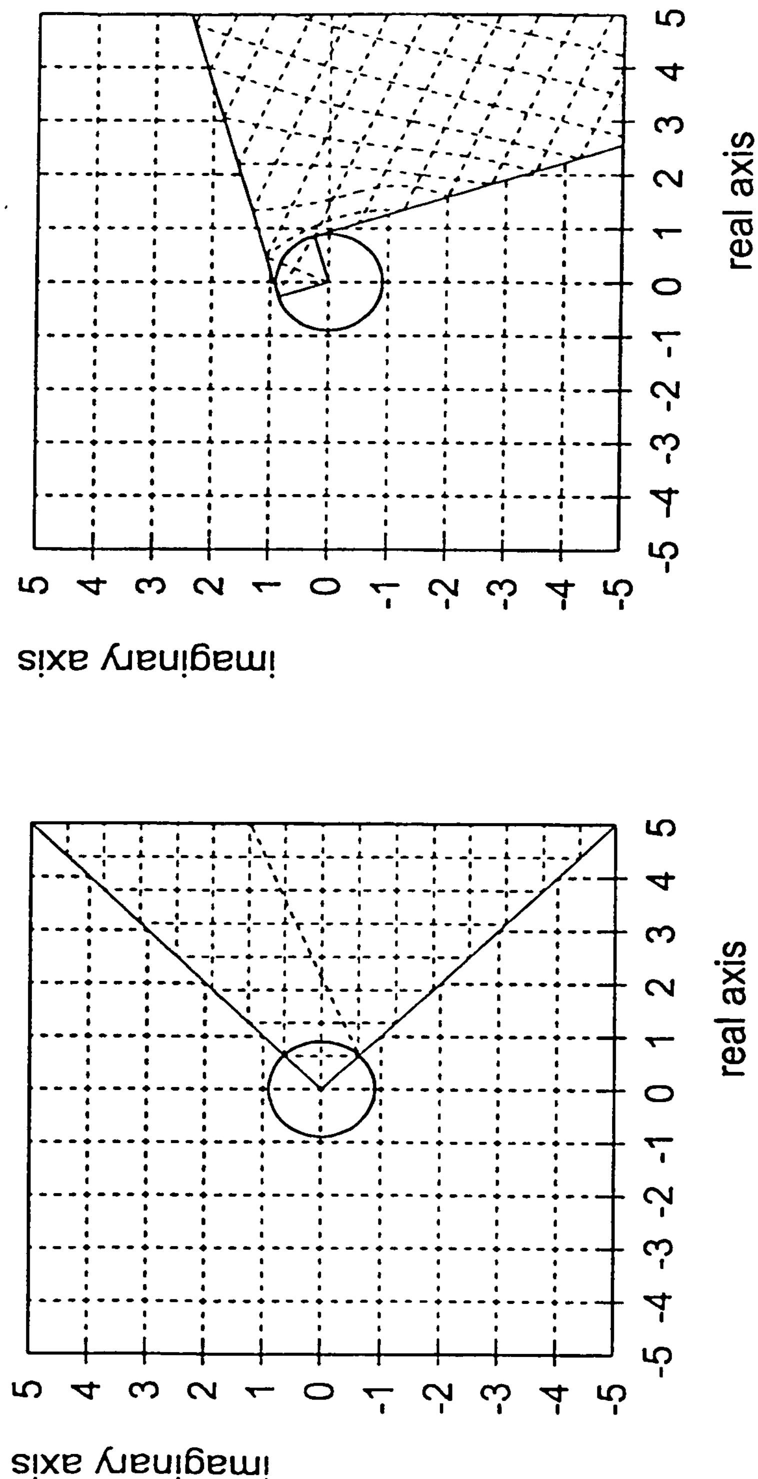
real axis
imaginary axis
5 4 3 2 1 0 -1 -2 -3 -4 -5
-5 -4 -3 -2 -1 0 1 2 3 4 5
real axis
imaginary axis
5 4 3 2 1 0 -1 -2 -3 -4 -5
-5 -4 -3 -2 -1 0 1 2 3 4 5

FIG.6

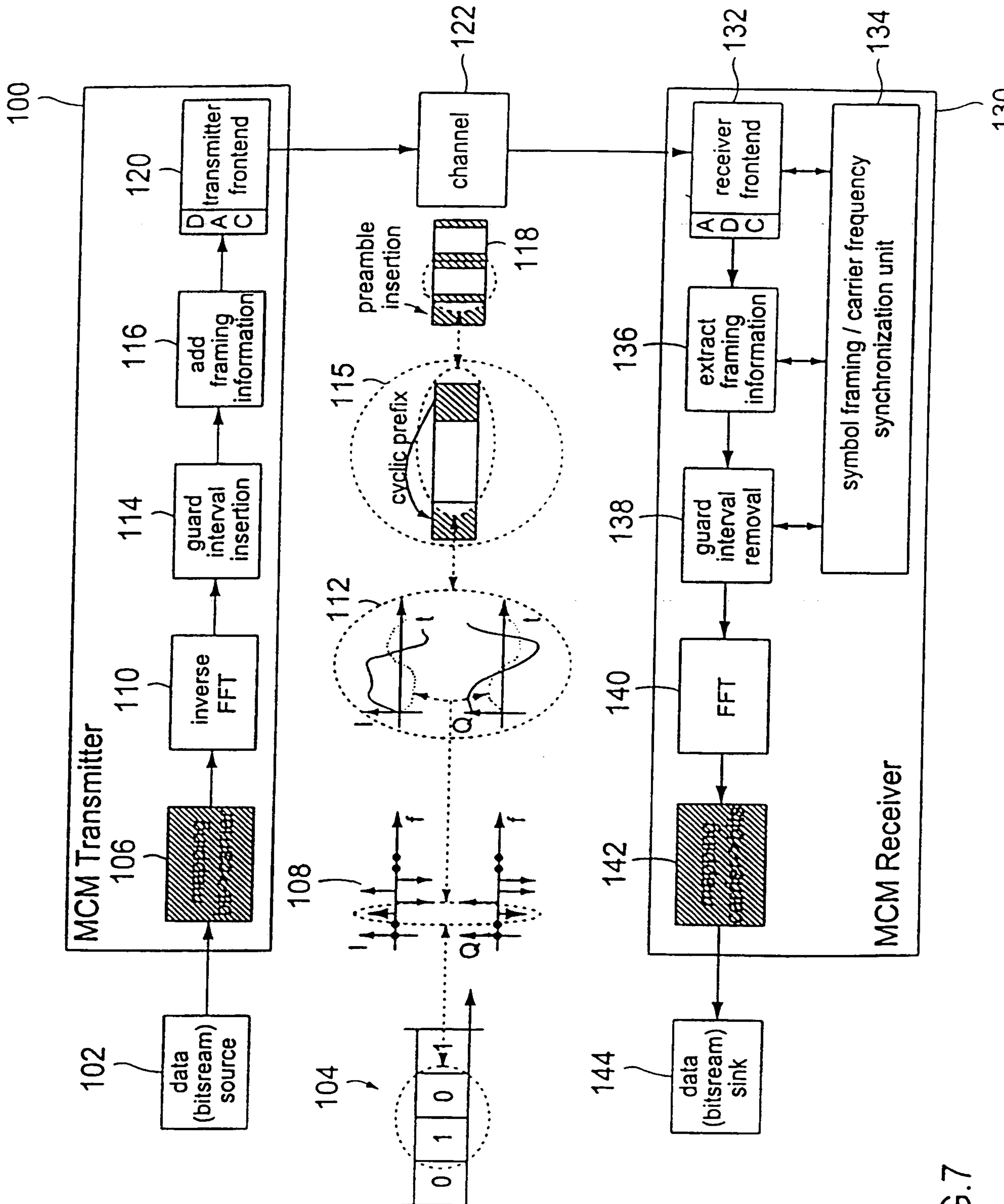
100
MCM Transmitter
102
data (bitsream) source
106
mapping bit->carrier
110
inverse FFT
114
guard interval insertion
116
add framing information
120
DAC
transmitter frontend
122
channel
104
0 1 0 1
108
I
Q
f
112
115
cyclic prefix
preamble insertion
118
130
MCM Receiver
132
receiver frontend
ADC
134
symbol framing / carrier frequency synchronization unit
136
extract framing information
138
guard interval removal
140
FFT
142
mapping carrier->bits
144
data (bitsream) sink

FIG.7

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 98/02167

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04L27/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MOOSE: "Differentially coded multi-frequency modulation for digital communications" SIGNAL PROCESSING THEORIES AND APPLICATIONS, 18 - 21 September 1990, pages 1807-1810, XP000365916 Amsterdam, NL see page 1807, left-hand column, paragraph 1 see page 1808, right-hand column, paragraph 4 ---	1-24, 30-49
A	WO 92 05646 A (NATIONAL TRANSCOMMUNICATIONS) 2 April 1992 see page 9, line 1 - line 14 ---	25-29, 50-58

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
5 January 1999	12/01/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Scriven, P

1

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 98/02167

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
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A	MOOSE: "A technique for orthogonal frequency division multiplexing frequency offset correction" IEEE TRANSACTIONS ON COMMUNICATIONS., vol. 42, no. 10, October 1994, pages 2908-2914, XP002019915 NEW YORK, US cited in the application see page 2910, right-hand column, paragraph 1 - page 2911, right-hand column, paragraph 4 ---	25,26, 50,51,53
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